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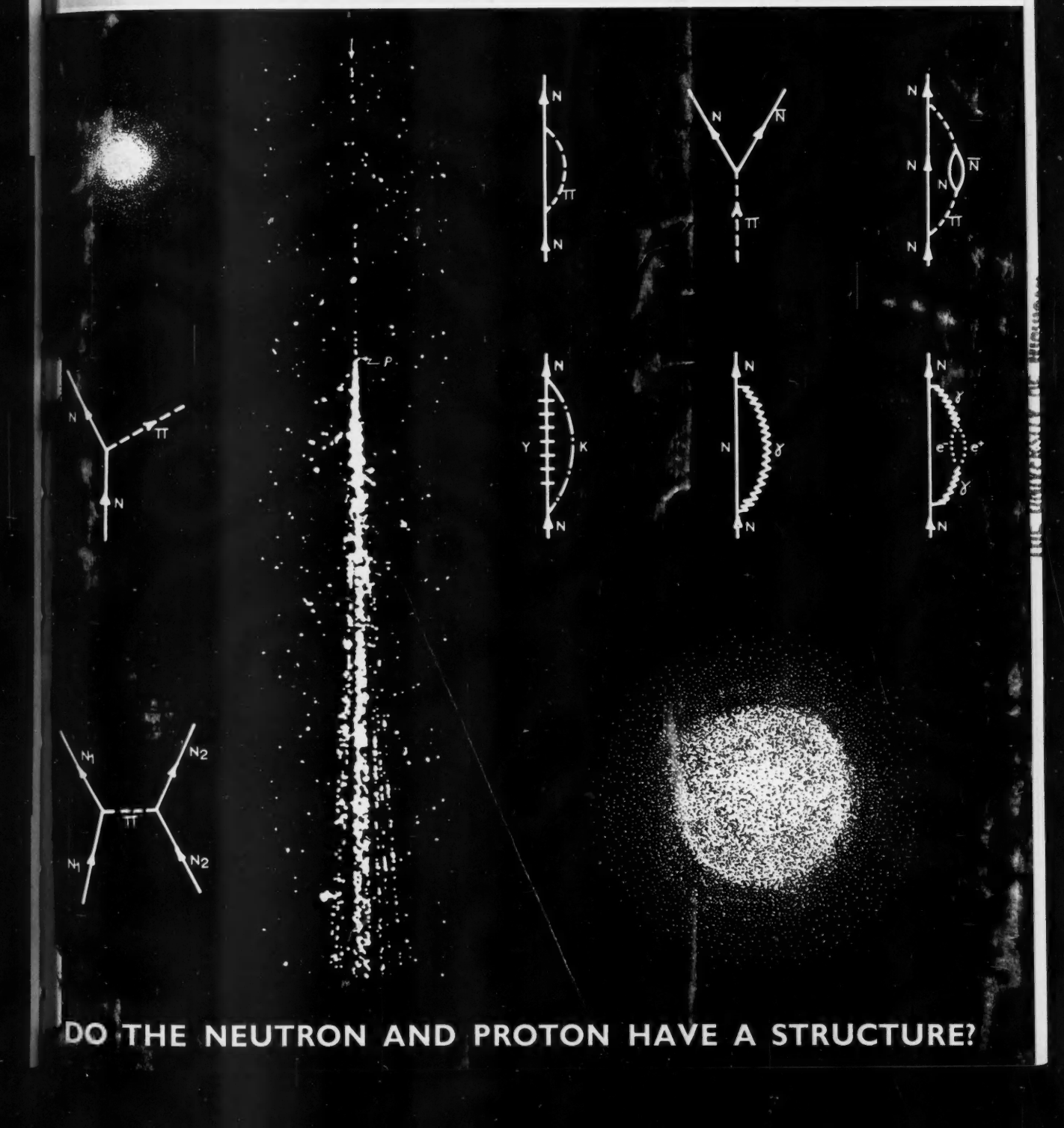

DO THE NEUTRON AND PROTON HAVE A STRUCTURE?

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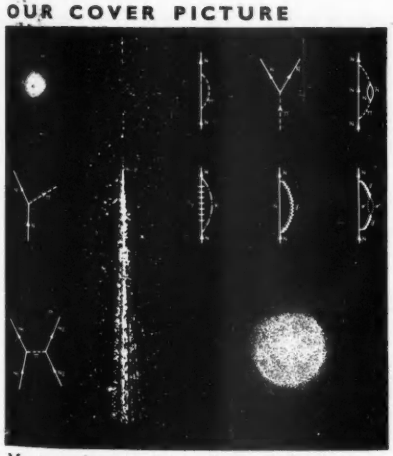
OUR COVER PICTURE



Montage of particle interactions and the charge distributions in nuclei of hydrogen (one proton) and gold (79 protons and 118 neutrons).

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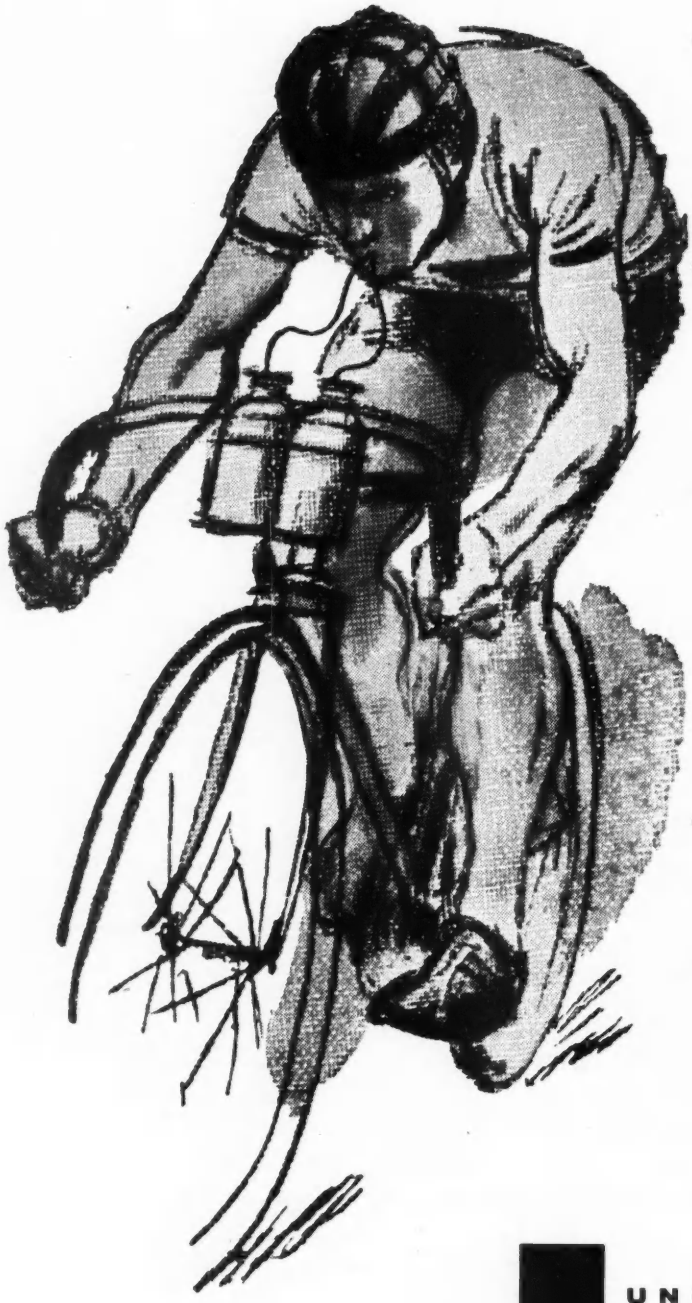
Autoxidation of Fats



Fats oxidise readily. It is good in a way that they do so for it makes them a useful source of bodily energy. It is not so good in another for it makes them prone to rancidity and other unpalatable oxidative changes. It is important then to try to restrict oxidation to its beneficial role, but one cannot do this effectively without some understanding of the mechanics involved. Early efforts to acquire this understanding culminated in Farmer's hypothesis of a free radical reaction, leading to attack at a methylene group adjacent to a double bond and the formation of a hydroperoxide. Such compounds have since been isolated and identified, in support of the hypothesis. Hydroperoxides are labile substances, however, and in normal circumstances they react further—possibly again by free radical mechanisms—to form either innocuous hydroxy compounds or obnoxious carbonyls. Mechanisms have been postulated, but the conditions under which one or another will operate have not been determined satisfactorily. These are matters of increasing importance in present world economy. Unilever is probably the largest single user of fats so, in Unilever Research, Crossley and his colleagues are working to resolve the problems that remain; studying model systems, relating cause and effect, and establishing conditions for stability of the many types of fats which Unilever use.

UNILEVER RESEARCH

THE PROGRESS OF SCIENCE

IAEA MEETING ON BIOLOGICAL EFFECTS OF ATOMIC RADIATION

New research findings on the biological effects of atomic radiation were reported at a meeting in Vienna early last month under the sponsorship of the International Atomic Energy Agency. Twenty-eight biologists from fifteen countries participated.

One of the subjects discussed was the mechanism (still unknown) by which radiation damages the cell—a fundamental problem in radiobiological research. Although the effects of radiation have been studied in great detail, the exact process by which it is caused is still not clear. One of the theories discussed at length at the Vienna meeting was that radiation leads to the release of enzymes (catalytic substances produced by living cells) within the cell which, in turn, cause destructive chemical changes in the cell structure. Another theory discussed dealt with the modification of the permeability of cell membranes, an action which may be associated with enzyme release.

Some attention was given to the problem of recovery from acute radiation injury and to possible ways of preventing undesirable secondary effects from the grafting of bone marrow or equivalent tissue.

During the discussion on the use of radiation to preserve food, it was disclosed that the combined use of heat and low-level radiation appeared particularly promising. If developments in this direction prove practical, it would obviate the need for using very large doses of radiation for sterilisation, avoiding such undesirable side effects as changes in taste and appearance.

A report was also given on the use of radiation to produce useful mutations in plants. In the field of drugs, there was a discussion on the first results of experiments to produce polio vaccine by using a combination of radiation and chemical agents to inactivate the virus. The possibility of using radiation for virus research was also mentioned; one approach suggested was the irradiation of the cells of experimental animals to make them accept human viruses so that the growth, behaviour, and control of the viruses could effectively be studied.

FISH, PENGUINS, AND BIOLOGICAL CLOCKS AT THE ANTARCTIC

How do the fish at the Antarctic live at temperatures that would kill most other species? This question is being studied at a new U.S.A. biological laboratory at McMurdo Sound that is headed by Dr D. E. Wohlschlag of Stanford University.

Studies in the north polar region have shown that the metabolic rates of Arctic fish are twenty to thirty times greater than those of tropical fish. No one is certain how this rate is produced but Dr Wohlschlag believes the endocrine glands may play a prominent role; for some reason, the pituitaries and other endocrines might have increased their output of hormones which in turn would raise the level of metabolism or chemical activities in parts of the fishes bodies. Among the various fish being studied at McMurdo Sound is the *Chaenichthyid*, the only vertebrate known to have white blood. Discovered in 1954 by a Norwegian biologist, it does not appear to be unusual in any other respect; it just has no haemoglobin in its blood. (Haemoglobin has been regarded as the only means by which oxygen is carried from the lungs or gills through the blood to the cells.)

Among the other animals being studied in the Antarctic by U.S. scientists is the *Adelie* penguin. A two-year field study of this species—one of the most intensive ever made—will be completed soon. Thousands have been banded and observations are being made on their mating habits, parental behaviour, weight, moulting habits, etc. Minute radio transmitters fitted into eggs have shown that the average incubation temperature is 92·7°F, despite the intense cold.

Experiments to determine whether or not the earth's rotation has any effect on biological "clocks" have also been going on in the Antarctic. Rodents, fruit flies, fungi, and soya beans have been placed on a small turn-table directly over the South Pole and rotated so as to cancel out the earth's rotation. No noticeable effect has been observed so far on the rhythms of these organisms.

CAN VENUS BE MADE HABITABLE?

Hot, arid, calm, and overcast, the surface of Venus appears inhospitable for human habitation at the present time. If the microwave emission measured from Venus is coming from the surface, the surface temperature must be about 600°K (520°F). At such temperatures, no known terrestrial microorganisms can survive for more than a few minutes; proteins are denatured, deoxyribonucleic acid is depolymerised, and even small organic molecules are dissociated in short periods of time. As temperatures at the poles of Venus are probably not more than 100°K (180°F) cooler than the mean planetary temperatures, it appears quite certain that terrestrial organisms deposited anywhere on the surface of the planet would quickly be killed.

These are some of the conclusions reached by Dr. Carl Sagan of the University of California (Berkeley) on the basis of a study described in *Science*, the journal of the American Association for the Advancement of Science.

According to Dr Sagan, the microwave data suggest that the surface of Venus closely resembles terrestrial desert wastelands. The temperatures are too high to permit such previously suggested possibilities as carboniferous swamps, a planetary oil field, or a global ocean of carbonated water; the desert suggested by St. John and Nicholson in 1922 is still roughly consistent with the data, however. From the surface of Venus, we might see the sun only dimly. The sky would be completely overcast perhaps 90% of the time and the high-altitude white clouds would sometimes appear reddened by dust. The atmosphere may be transparent in the near ultraviolet.

With such high temperatures, there can be no liquid water at the surface of this planet and the existence of indigenous surface organisms at the present time appears very unlikely, Dr Sagan states. If life based upon carbon-hydrogen-oxygen-nitrogen chemistry ever developed in the early history of Venus, it must subsequently have evolved to sub-surface or atmospheric ecological niches. Since there can have been no appreciable periods of time when Venus had both extensive bodies of water and surface temperatures below the boiling point of water, however, it is unlikely that life ever arose on that planet.

The California scientist goes on to describe a means by which Venus can be made habitable for earth men.

It is necessary to lower the surface temperature and increase the partial pressure of molecular oxygen; both ends could be accomplished if a means were found to dissociate carbon dioxide to oxygen and elemental carbon. Even if ordinary green plants could grow on the surface, the problem would not be solved, because the oxygen evolved in photosynthesis derives from water and the amount of carbon dioxide in the atmosphere of Venus is more than 1000 times greater than the amount of water vapour.

An organism is needed which can photosynthesise in the high atmosphere of Venus according to the equation

$$CO_2 + H_2O + \text{light} \rightarrow (CH_2O) + O_2,$$

the oxygen arising from the water. In time, the organisms would be carried to lower atmospheric levels where, because of the higher temperatures, they would be roasted, decomposing ideally according to the equation.

$$(CH_2O) + \text{heat} \rightarrow C + H_2O$$

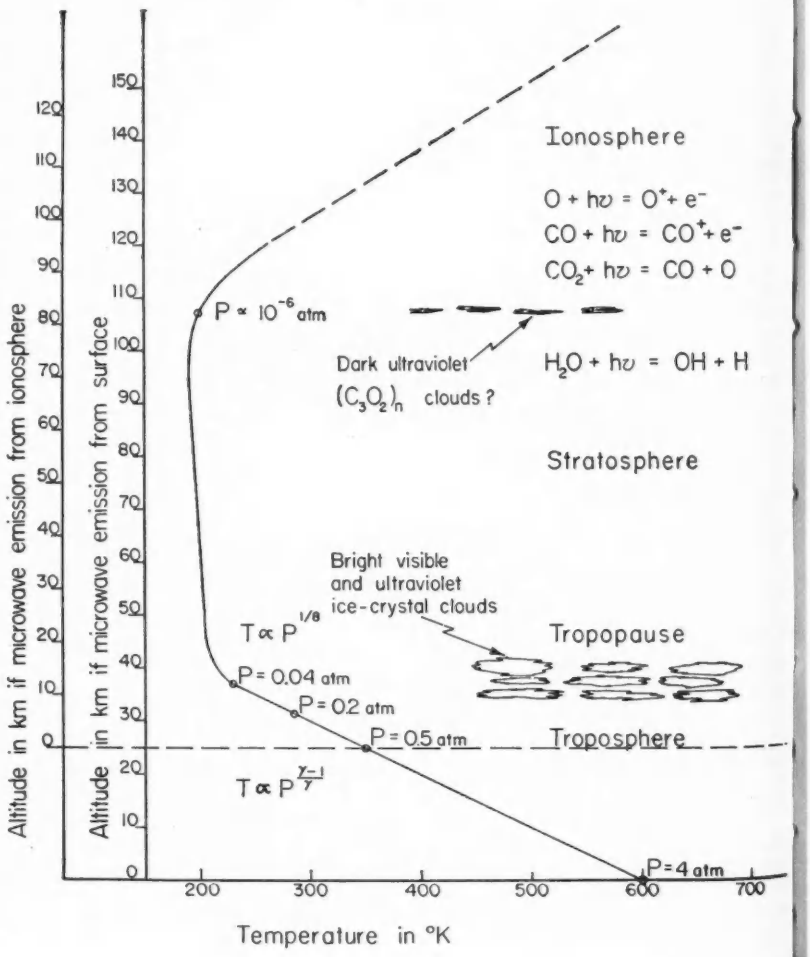
Although the oxygen is derived from water, the overall effect would be to restore the water metabolised in photosynthesis to the atmosphere, and dissociate carbon dioxide to carbon and oxygen.

Before such a scheme can be seriously considered, Dr Sagan cautions, much more information must be acquired about the composition and meteorology of the Cytherean (Venus) atmosphere and extensive laboratory biological investigations must be performed. Nevertheless, some tentative specifications can be entertained at the present time. In order to have appreciable photosynthesis before thermal dissociation, the life form deposited must be a microorganism. Since there is no liquid water anywhere on Venus, the organism must be able to utilise water vapour (from the atmosphere) or ice crystals (from the cloud layer). The only known microorganisms which photosynthesise evolving molecular oxygen are the algae. It would be desirable to have an organism with resistance to extremes of temperature. Blue-green algae are known to survive immersion in liquid nitrogen, and some forms ordinarily live in hot springs at 80°C. Since there is little likelihood that the microorganisms would find nitrogen in the form of nitrates or ammonia in the atmosphere of Venus, they would have to be able to fix molecular nitrogen in the atmosphere. The only photosynthetic, nitrogen-fixing, oxygen-evolving, temperature-resistant aerial microorganisms are the blue-green algae, primarily of the Nostocaceae family.

Extensive laboratory experiments should be performed on the ecology of the algae in simulated Cytherean environments, Dr Sagan states. It is necessary to know whether the algae will be able to reproduce prior to thermal decomposition; whether a complete aerial existence is possible, or if they require the cloud ice-crystals as a substratum; whether a strain can be found which will photosynthesize at low temperatures and high ultraviolet fluxes; whether trace metal requirements can be supplied by meteoritic infall, or whether metals must be provided artificially; and what the products of slow thermal decomposition may be. But it is conceivable that these problems can be solved, and that the microbiological re-engineering of Venus will become possible. Such a step should be taken only after the present Cytherean environment has been thoroughly explored, to prevent the irreparable loss of unique scientific information. It might be advisable to find suitable controls for algae, because in the absence of predators and competitors the algae might reproduce at a geometric rate and the entire conversion of carbon dioxide would then be accomplished in relatively short periods of time.

Ideally, one can envisage the seeding of the upper Cytherean atmosphere with appropriate strains of Nostocaceae after exhaustive studies have been performed on the existing environment of Venus. As the carbon dioxide content of the atmosphere falls, the greenhouse effect is rendered less efficient and the surface temperature falls. After the atmospheric temperatures decline sufficiently, the decreasing rate of algal decomposition will

Preliminary temperature profile of the atmosphere of Venus. Two altitude scales are given, corresponding to the alternative sources of the 600°K microwave brightness temperatures. Troposphere pressures are computed from the 8000-Å band intensities and the adiabatic gradient; the pressure at the base of the ionosphere is derived from occultation data. The altitude of the tropopause cloud layer is bracketed as shown, but the depth of the clouds should be much less than is indicated. On the ionospheric model, the tropopause cloud layer could not be composed of water. If there is nitrogen in the Cytherean atmosphere, nitrogen ionization should occur in the higher atmosphere in addition to the processes shown. The slope of the ionospheric temperature profile is schematic only.
(*Reprinted from* Science, *with permission*)



reduce the water abundance slightly and permit the surface to cool below the boiling point of water. At this time, the original mechanism should become inoperative, because the algae are no longer thermally decomposed, but now surface photosynthesis becomes possible. At somewhat lower temperatures, rain will reach the surface, and the Urey equilibrium will be initiated, further reducing the atmospheric content of carbon dioxide to terrestrial values. With a few centimeters of precipitable water in the air, surface temperatures somewhere near room temperature, a breathable atmosphere, and terrestrial microflora awaiting the next ecological succession, Venus will have become a much less forbidding environment than it appears to be at present. Hopefully, by that time we will know with more certainty whether to send a paleobotanist, a mineralogist, a petroleum geologist, or a deep-sea diver.

BEHAVIOUR OF ANIMALS, MEN, AND MACHINES

The unities underlying the behaviour of animals, men, and machines were brought into clearer focus at a symposium held in Dayton, Ohio, under the sponsorship of the United States Air Force (Wright Air Development Division). Thirty invited speakers reported new developments concerning (*a*) methods of information handling used by living systems and (*b*) artificial models of such systems.

At the start, H. E. Savely of the Air Force Office of Scientific Research pointed out three aspects of living systems which are worthy of study for incorporation into artificial systems: (i) the extreme sensitivity of certain receptor organs—for example, the ability of certain fish to detect a change in the electric field in the water around them of as little as 0·003 μv/mm.; (ii) the ability of even simple living brains to integrate the activity of many sensor and effector organs; (iii) the ability to retrieve information rapidly in the central nervous system; and (iv) the ability to store information at molecular levels, even for periods of generations, as in the chromosomes. An example of the successful use of a living system as a prototype for an artificial system is the application in an optical ground-speed indicator for aeroplanes of the simple principle in the beetle's visual system that provides information on velocity.

H. E. Savely cautioned (i) that as long as we lack fundamental understanding of the laws of organised complexity, it may not be possible to duplicate the living system; (ii) that nature is limited simply to building on and modifying pre-existing systems and that the living system therefore may not provide the most economical approach to a particular information-handling problem; and (iii) that it is common for the physical scientist to think that he can take a quick look at some biological system, work out the principles in a very short time, and then apply them to the design of some artificial system. Not only is he mistaken in this belief but he is very much like Brer Rabbit attacking the Tar Baby. The harder he attacks the problems of biology the more deeply does he become enmeshed, so that he soon finds himself unable to drop them.

An analysis of the relatively simple servomechanism controlling the size of the pupil of the human eye was presented by Laurence Stark, now of the Massachusetts Institute of Technology. This paper and one other were the only reports dealing directly with the information-handling mechanisms of living systems—evidence perhaps of the difficulty of such an approach. The other talks dealt with the design of artificial systems. E. E. Loebner of RCA Research Laboratories pointed out that man, because he has few outputs (muscles), has built only a few information inputs into the gear he controls, to match his few outputs. This restriction on the number of inputs has been carried over into equipment not under human control. It would often be preferable to give such equipment multiple inputs, such as man has in his sense organs.

The general logical operations that a computer must perform in order to behave like an organism were described by Peter M. Kelly of Aeronutronics. It must take inputs from a sensory field, code them into groups, act on them by some internal logic, code the outputs, and carry out responses in terms of this output code. The coding of the sensory input to the internal logic can be fixed in advance—that is, preorganised. It is also possible to design machines which are self-organised—that is, capable of learning how to code their sensory input and their output so as to achieve the desired responses to particular sensory situations. Kelly, and also Walter Reitman of Carnegie Institute of Technology, discussed the design of such machines and gave examples of existing machines in which the two types of design are used. (Could it be that when we intuitively judge one type of organism to have more "consciousness" than another, the distinction in physical terms is that it has a greater capacity for self-organisation?)

W. P. Tanner of the University of Michigan argued that the human being is not completely preorganised so as to give a fixed response for a particular sensory input but is capable of self-organisation. Therefore, the human being subjected to psychophysical tests should not be considered to have a sensory threshold but should be treated as a computer which is testing the statistics of the test situation and making decisions which optimise some aspect of that situation. Tanner is analysing such performances of human beings in auditory test situations.

The problem of designing a machine which can differentiate or recognise one out of all possible sensory functions was discussed by Seymour Papart, of the National Physical Laboratory, Teddington, England. The problem is simplified by the fact (i) that the input functions possible are only a portion of all functions, and (ii) that as the number of dimensions of the input functions increase, the chance of separating any two input functions increases, even with a simple machine. He has roughly estimated that one human being during his lifetime could learn up to 10^8 particles of information. This much learning could be handled by any of the systems of self-organisation described at the symposium. (Compare this estimate with the estimate of 10^{15} made some years ago by W. S. McCulloch and of 10^{13} to 10^{15} made by H. von Foerster.)

Artificial devices which recognise patterns, including one device capable of recognising cancerous cells under the microscope, were mentioned by P. Metzelaar of Space Technology Laboratories. Some machines have given performance superior to the human—for example, a checker-playing programme for the IBM 704 computer, Other machines have been designed that can predict the future ot a sequence from its past. Metzelaar suggested that if the design problems can be solved, the future machine will do preliminary pattern transformations on its sensory inputs in order to reduce the amount of information that must be handled and stored. It will also be able to consider its sensory input in either gross outline or fine detail and know which type of consideration is needed, decide how to divide its attention among its different sensory inputs, and know which of various recognition mechanisms it should use.

In a talk that was as remarkable for its witty asides as for its lucid exposition, A. Novikoff, of Stanford Research Institute briefly described integral geometry and illustrated its use in the design of pattern-recognising devices. One theoretical device is able to distinguish patterns, regardless of their rotation or translation in the visual field, by differences in the frequency

continued on page 225

NEUTRONS AND PROTONS
—DO THEY HAVE A STRUCTURE?—

E. H. S. BURHOP

If neutrons and protons have a finite structure, of what are they composed? Are they really fundamental particles or are they made of something more basic, pointing to a new physics? The subject promises a large number of surprises in the future

Protons, neutrons, and electrons are sometimes referred to as the building bricks of matter—the fundamental particles from which all matter is formed. The neutrons and protons, held together by very powerful attractive forces, form the tiny massive nucleus of the atom around which the electrons move.

But what is meant when one refers to a particle as being fundamental? Are electrons, protons, and neutrons points or do they have a finite size? And if they have a finite structure, of what are they composed? Does it imply that they are not really fundamental at all, but are made of something even more basic, pointing to a new physics beyond the scope of present means of investigation?

In the fifteen years since the end of the war the number of particles classed as fundamental has multiplied many times. There are now some thirty of them,* mostly unstable with a lifetime of a hundred millionth of a second or less. It is natural to speculate that these may not all be true fundamental particles but may be related to the modes of existence of some even more fundamental entity. The answer to such questions may well come from studying the structure of the proton and neutron, and modern technical developments have made such studies possible.

SIZES OF THE SUB-ATOMIC PARTICLES

Questions about the extent of fundamental particles are not new. It is more than sixty years since J. J. Thomson pondered them for the electron. Could it be a point charge? It is well known from classical electricity that the potential energy of a sphere of radius a, having a charge e spread over the surface is $e^2/2a$. For a point charge, the potential energy would be infinite. Using Einstein's famous relation $E=mc^2$, where m is the mass equivalent to energy E, and c is the velocity of light, the minimum radius of an electron of mass m comes to be $e^2/2mc^2$, or $1{\cdot}4\times10^{-13}$ cm. If the same arguments were applied to a proton, its minimum radius would be much smaller, namely $7{\cdot}6\times10^{-17}$ cm.

Many experiments have shown that the electron is much smaller than suggested by this simple calculation. To this day we don't know how small—or indeed whether it has finite extension at all—although a great deal of thought is going into devising experiments that might show up effects of the finite size of the electron. One thing appears certain: the mass of the electron cannot be primarily electrostatic in origin, as suggested by Thomson's speculations. We also know that the proton has an extension in space much larger than suggested by the naïve classical picture. Powerful experimental techniques, applied particularly by Hofstadter and his colleagues at Stanford University in California, have shown that both the proton and neutron have a structure in space extending about 10^{-13} cm. from their centre. The exploration of details of this structure is one of the most fascinating tasks facing the high-energy physicist today.

PROBING THE PROTON AND NEUTRON

The technique used at Stanford employs high-energy electrons as probes of nucleon structure.* It is quite an old technique in principle and has been used extensively in the exploration of molecular structure, electrons with energies of some tens of thousands of electron volts being found most convenient. The nucleons themselves are so small, on the other hand, that the probing of their structure requires electrons with energies of many hundreds of million electron volts (MeV). Electrons of such energies have only been available in recent years as a result of the development of high-energy accelerators. The technique developed for probing the structure of nucleons makes use of the interference of coherent waves that have reached a point by different paths and so differ in phase, just as in the familiar interference experiments with light. In the present case, however, the waves are the de Broglie electron waves. If a wave is scattered by an object of finite extent, the amplitude scattered in a given direction will be found by adding together the contributions from wavelets scattered by all the different portions of the scatterer. There will be differences in path length between these different wavelets, and therefore differences in phase (*see* Fig. 1). As a result, the scattered amplitude in any direction will generally be less than would have been the case had all the scattering material been concentrated at a point. The ratio of these two amplitudes is referred to as the form factor. It will depend on the angle of scattering and also on the wavelength of the waves. If the magnitude of the form factor is known over a large range of angles and wavelengths, the structure of the scatterer, or rather, its density distribution, can be derived.

Electrons can be scattered by the electric charge carried by a proton. A beam of electrons behaves like a wave, having a wavelength which depends on

* This number would be about halved if we classified particle and anti-particle together (for example, electron and positron, proton and anti-proton, etc.).

* The term "nucleon" is used for either proton or neutron when we do not wish to specify them explicitly.

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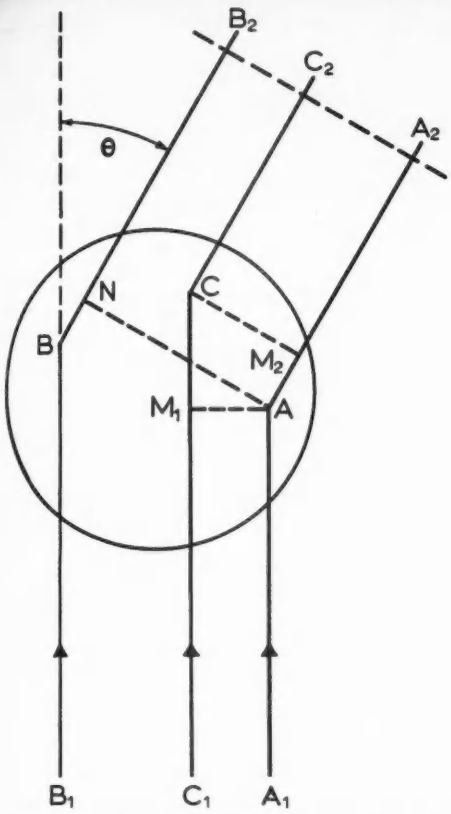


FIG. 1. Scattering of a beam of waves by an extended scatterer. B, C, and A are points on the front of the wave before scattering. The wavelets that combine to produce the wave scattered through the angle θ have different path-lengths and hence different phases. For example, the phase of the wavelet arriving at C_2 after scattering at C is behind that which arrives at A_2 after scattering at A by the amount $2\pi(CM_1—AM_2)\lambda$, where λ is the wavelength. The resultant amplitude of the wave scattered in this direction is therefore less than it would be if all the scattering material were concentrated at a point, because of these differences in phase.

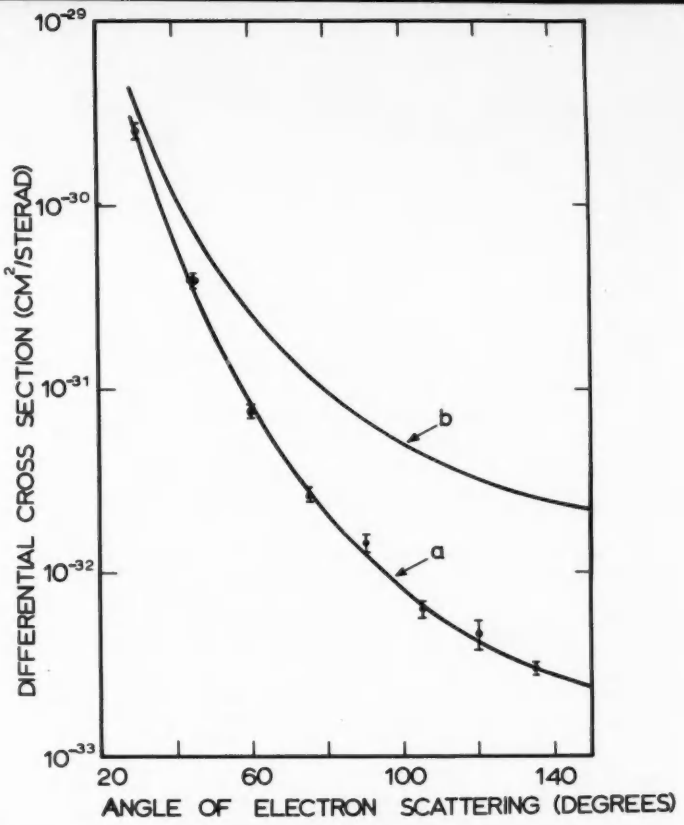


FIG. 2. Angular distribution of 550 MeV electrons scattered by protons. Curve (*a*) is drawn through the experimental points. Curve (*b*) is the angular distribution to be expected if all the charge and magnetism of the proton were concentrated at a point. The differential cross-section measures the number of particles scattered through the scattering angle indicated per unit solid angle (sterad) for an incident beam containing one electron/sq. cm. Note that the vertical scale is logarithmic.

its velocity—the so-called de Broglie wavelength: $\lambda=h/v$, where m is the mass, v is the velocity of the electrons, and h is Planck's constant. If, then, the electric charge on a proton is not concentrated at a point but is of a finite extent, it should be possible to derive the size of the proton and the way the charge is distributed over it by measuring the form factor for electrons of different velocities scattered through different angles by protons.

To use this method effectively, the wavelength of the electrons should not be too much larger than the size of the proton. If we assume that interference effects are important when the wavelength is about equal to the perimeter of the proton or less, then electrons with energies of at least 300 MeV are needed, as the radius of the proton turns out to be about 8×10^{-14} cm. It thus becomes readily apparent that research of this kind requires very energetic electrons. At Stanford an electron linear accelerator has been built to produce electrons with energies as high as 1000 MeV.

The neutron, as is well known, has no net electric charge. This by no means implies that a neutron has no charge distribution, however. It could happen that charges of different sign are to be found in different regions of this particle in such a way that the total charge vanishes.

Since both the proton and neutron behave like small magnets, some of the scattering they produce when bombarded by an electron stream can be attributed to their magnetic fields. As the scattering distribution would depend on whether the magenetic moment is spread out over the whole nucleon or concentrated at a point at the centre, scattering experiments can give considerable information on their structure. If the magnetic moment is spread out, it is interesting to find out if the distribution is the same as the electric charge distribution. We can, in fact, think of form factors for both electric charge and magnetic intensity. We call these four form factors F_1^P, F_2^P, F_1^N, F_2^N, the suffices 1 and 2 referring to the electric charge and magnetic moment distribution respectively.

The experimental set-up used to study the shape of the proton is very simple in principle. Fast electrons are made to hit a target of hydrogen (which may be either hydrogen gas at a very high pressure, say 150 atmospheres, or liquid hydrogen) and the fraction of incident electrons scattered through various angles is measured, using

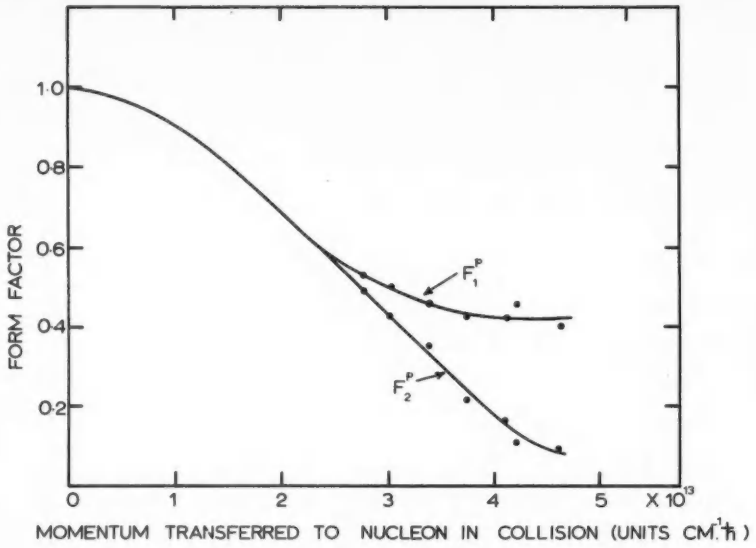


FIG. 3. Variation of the proton form factors for electric charge F_1^P and magnetic momentum F_2^P with the closeness of the collision as measured by the momentum q transferred to the scattering proton. F_1^P is the ratio of the amplitude of the electron wave scattered by the electric charge of the proton to the value it would have if the charge were all concentrated at a point. Similarly, F_2^P is the ratio of the amplitude of the electron wave scattered by the magnetic moment of the proton to the ratio it would have if all the magnetism were concentrated at a point.

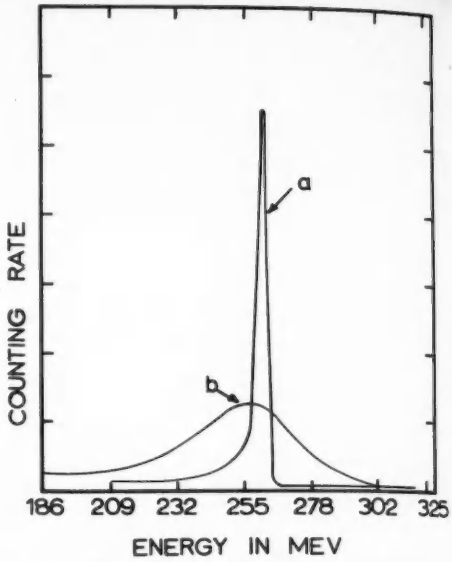


FIG. 4. Energy distribution of 500 MeV electrons scattered through an angle of 135° in (*a*) hydrogen and (*b*) deuterium. The distribution is broadened in deuterium because the neutron and proton in the deuteron possess an internal momentum. By comparing the area under the two curves, the contribution of the scattering by the neutron in the deuteron can be estimated.

special counters. The kind of result obtained is illustrated in Fig. 2. Curve (*b*) gives the distribution to be expected if the proton had its whole charge and magnetic moment concentrated at its centre. Curve (*a*) through the experimental points shows there are fewer scattered electrons at large angles than would be expected for a point scatterer, indicating that the charge and magnetic moment of the proton are distributed over a finite volume.

It is of great interest to try to separate out from the observed scattering distribution the effect of the spreading out of both the electric charge and magnetic moment. This can be done quite effectively by comparing the scattering of electrons of different energies scattered through different angles in such a way that the electrons communicate the same amount of momentum to the protons they hit. It turns out that the effect of the charge distribution is dominant in influencing the scattering at small angles while that of the magnetic distribution is most effective at large angles.

Fig. 3 shows the form factors, F_1^P, F_2^P separated out and plotted as a function of q, the momentum communicated by the electron to the proton. It is seen that over quite a large range of q the two form factors are indistinguishable, but at very large values of q, F_2^P falls markedly below F_1^P. The larger the value of q the closer to the centre of the nucleon do the incident electrons probe. It is concluded, therefore, that the distribution of electric charge and magnetic moment is the same over most of the nucleon but that there is, in addition, a concentrated dense core of electric charge near the centre of the nucleon with no corresponding dense core of magnetic moment distribution. Outside the core region the proton behaves as though both its charge density and magnetic intensity decrease, with a mean radius of about 0·80 fermis (a fermi is 10^{-13} cm.).

It is not possible to study electron-neutron scattering directly since a pure neutron gas cannot be obtained, but Hofstadter has found it indirectly by measuring the inelastic scattering of fast electrons by deuterons. The inelastic scattering corresponds to collisions in which the deuteron is broken up into its constituents, a proton and a neutron. The scattering can be interpreted as a combination of two parts, one due to the direct collision between the incident electron and a proton, and the other to an electron-neutron collision.

Electrons scattered through a given angle in deuterium gas are distributed over a range of energies. This is because the neutron and proton in the deuteron are in motion relative to their common centre of mass, so that the electrons are scattered by a target in random motion. In Fig. 4 the energy distribution of electrons scattered through a fixed angle from deuterium is compared with that from hydrogen. The area under the curve represents the total number of electrons scattered into the given angle from the neutrons and protons in the deuterons. Knowing from the previous work the number scattered from the protons, the number scattered in a given direction from the neutrons can be calculated. The electric form factor F_1^N and the magnetic form factor F_2^N for the neutron can then be derived. The neutron form factors have to be determined in this indirect way and are therefore far less accurate than the corresponding proton form factors. Nevertheless, they appear to indicate that approximately $F_2^N = -F_2^P$, while F_1^N is small for all values of q. Fig. 5 gives graphically an impression of the kind of charge density and magnetic intensity distributions for both proton and neutron suggested by the experiments. The density of the shading is intended to indicate the density of charge. Outside the central core of, perhaps, 0·3 or 0·4 fermis radius, the

charge distribution extends for more than 1 fermi, falling off exponentially with distance.

It is interesting, in passing, to compare this with the distribution of charge in a heavy nucleus containing many neutrons and protons. This distribution as determined by electron scattering is shown in Fig. 6 for a gold nucleus. The density is nearly constant over most of the nucleus but falls away in a comparatively short distance at the surface. The thickness of this "fringe" is found to be approximately the same for all nuclei—about 2·2 fermis. The radius (defined as the distance out to the point where the charge density is half its maximum) is proportional to the cube root of the number of nucleons (A) in the nucleus. This relationship ensures that the central portion of all nuclei except the lightest contain the same number of nucleons per unit volume. Indeed, the inner region of nuclei can be thought of as constituting a special type of matter (nuclear matter) that is characterised by a very high density—about 3×10^{14} gm. (or 300 million tons) per cu. cm.

The charge distribution in the case of large nuclei is due to the way in which the individual protons are distributed inside the nucleus. The charge (and magnetic moment) distribution in a single proton or neutron, on the other hand, is something much more fundamental. In the first place, it raises the question as to whether they should be considered fundamental particles at all. Does it not imply they are built from some even more fundamental entity? It is not necessary to make this inference.

THE MESON FIELD

The key to the understanding of the structure of nucleons lies in the fact that they interact with other nucleons; such interactions are believed to take place through the intermediary of a field—the meson field. In the quantum theory of any field, we must envisage

FIG. 5. The electric charge distribution due to the meson cloud of the proton. The graph gives an impression of the corresponding fall-off of charge density with distance from the centre of the proton.

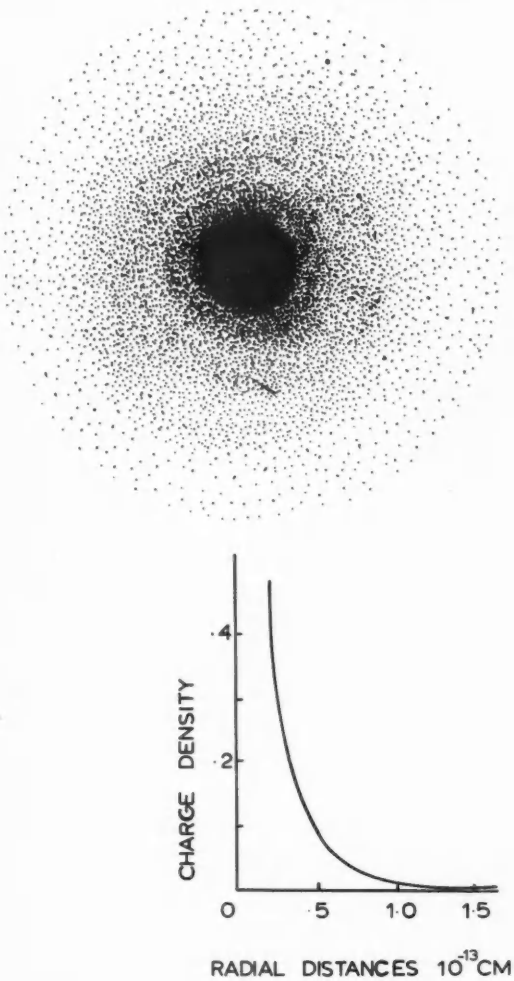
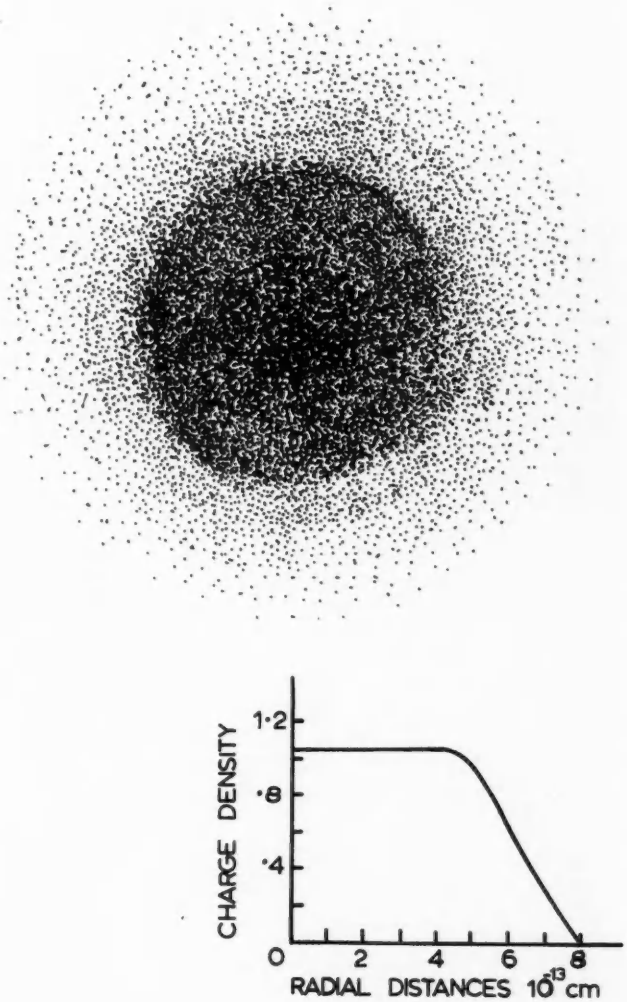


FIG. 6. The electric charge distribution on the nucleus of a gold atom.



the particles that generate the field (the "sources") as having a rather complex structure. Protons and neutrons interact with the electromagnetic field because of the charge or magnetic moment they carry, but they interact very much more strongly with the meson field. It is the meson field, in fact, that is responsible for the very strong nuclear forces between nucleons that hold them together to form nuclei of great stability. A proton (or neutron) is able to exchange energy (and momentum) with the meson field and it is found that when the energy interchanged is E, the corresponding momentum interchange p is always related to it according to the law

$$E^2=p^2c^2+m^2c^4 \qquad (1)$$

where c is the speed of light, and m is a constant. But this is exactly the relation between energy and momentum for a particle of mass m according to relativity theory. In the emission or absorption of energy between a nucleon and the meson field, therefore, it is just as if a particle of mass m were being emitted or absorbed. The mass m is found to be about 270 times the mass of an electron, and we call this "particle" a π-meson, or pion. It is the "quantum" of the meson field. By comparison, the corresponding quantum of the electromagnetic field—the photon of Planck and Einstein—has no mass because it is found that in the interchange of energy E and momentum p between a charged particle and the electromagnetic field, the relation $E=pc$ applies, corresponding to $m=o$ in the above equation.

When a π-meson is emitted from a nucleon into the meson field, the emitting particle recoils (Fig. 7*a*) since it has to change its momentum by an amount equal to the momentum transferred to the field (that is, the momentum of the π-meson). This means it will change its direction of motion. Similarly, a second nucleon near by which absorbs energy and momentum from the field (that is, absorbs the π-meson) will also recoil and change direction (Fig. 7*b*). It will appear then that the two nucleons have interacted and been scattered by each other. The quantum field theory interprets this interaction as arising from the transfer of a π-meson from one to the other through the intermediary of

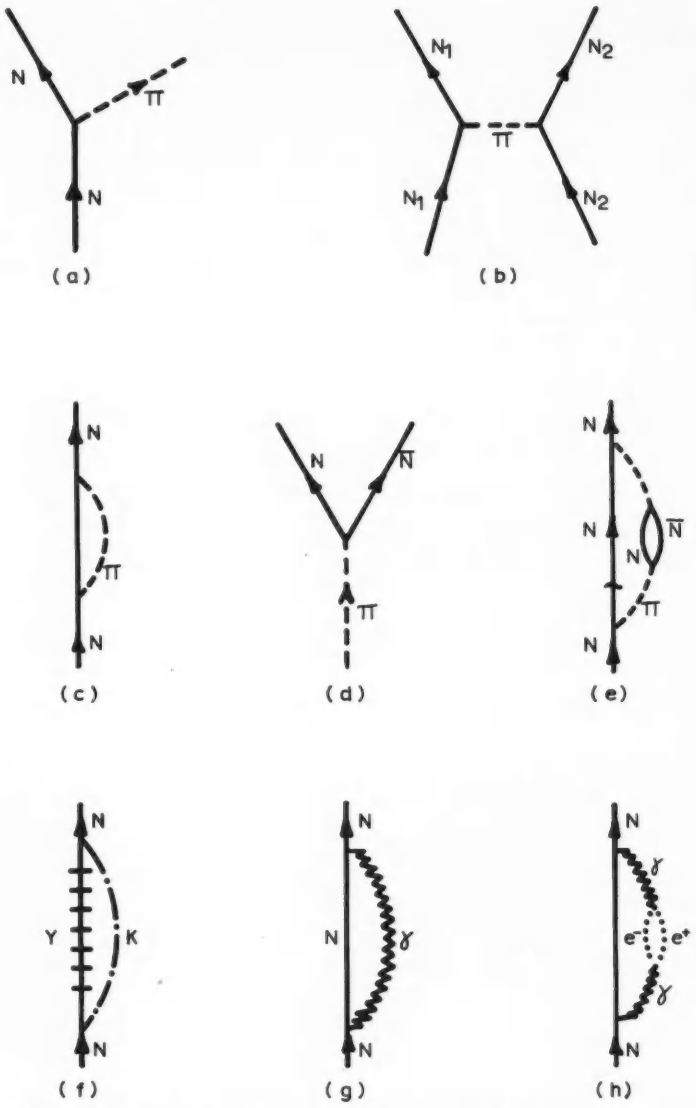


FIG. 7 illustrates the interaction processes between the nucleon and the meson and other fields. In these diagrams, the symbols have the following meanings: N, nucleon (either proton or neutron); $\bar{N}$, antinucleon (either antiproton or antineutron); π, π-meson; Y, hyperon; K, K-meson; δ, photon; e, electron; e^+, positron. In (*a*) a fast-moving nucleon emits a π-meson and becomes changed in energy and direction. The π-meson can only escape if a second nucleon is near by to take away some of the excess momentum and energy and enable the total energy and momentum to be conserved. In (*b*) a π-meson emitted by one nucleon is absorbed by a second nucleon as a result of which both change their direction of motion. In (*c*) a single nucleon emits a π-meson but it cannot escape and has to be reabsorbed after a time consistent with the uncertainty principle. The electric charges of these "virtual" π-mesons produce the extended charge distribution around the nucleon while their motion generates a distribution of magnetism around the nucleon. In (*d*) a π-meson has sufficient energy to transform into a nucleon-antinucleon pair. This pair can only escape if a second nucleon is near by to take away some of the excess energy and momentum. Case (*e*) is similar to (*c*) except that the virtual π-meson becomes transformed for part of its time into a nucleon-antinucleon pair which contributes to the transient cloud of particles around the nucleon. Case (*f*) shows how K mesons can appear in the cloud when the nucleon spends part of its time transformed into a hyperon. Virtual processes giving rise to the transient presence of photons and electron-positron pairs in the cloud are represented in (*g*) and (*h*) respectively.

the meson field. The masses of the nucleons are not altered by the process, of course, but their kinetic energies and momenta are changed.

If there is no second nucleon present to absorb the meson emitted by the first nucleon into the meson field, it will have to be eventually reabsorbed by the first nucleon. But how, one might ask, can an amount of energy represented by the rest mass of the meson be emitted into the field while leaving the mass of the nucleon unaltered? This would not be possible classically but can be understood in terms of quantum theory. The emission of the meson from the nucleon means that the energy of the system has fluctuated by an amount at least

$$\triangle E = m_\pi c^2$$

where m_π is the mass of the π-meson. According to quantum theory, momentum must be conserved in this process but the energy can fluctuate provided the fluctuation lasts for only a very short time. Indeed, this time, $\triangle t$, is related to $\triangle E$ by the Heisenberg Uncertainty Principle which states:

$$\triangle E \cdot \triangle t < \hbar$$

$$\text{or } \triangle t < \frac{\hbar}{m_\pi c^2}$$

where $\hbar = h/2_\pi$, h being Planck's constant.

During this time the meson cannot escape far from the proton from which it was emitted. Even if it is moving with the velocity of light the upper limit of the distance it can reach is $h/m_\pi c$, a distance of 1·4 fermis, known as the π-meson Compton wavelength. The proton cannot exist for long alone. It is always surrounded by a cloud of these so-called virtual mesons which are continually forming and dissolving again into the proton, rarely getting farther than about 1 fermi from it. The π-mesons are only one of many different kinds of virtual particles to be found in the cloud surrounding a proton. Some of the π-mesons may have sufficient energy actually to form a nucleon-antinucleon pair during their lifetime (Figs. 7*d* and 7*e*). For this to be possible, a meson would need to have an energy of at least $2MC$ where M is the mass of a nucleon. Using the same argument as before, such virtual nucleon-antinucleon pairs could last for a correspondingly shorter time than the lower-energy π-mesons, and they would not be found at distances greater than 0·1 fermi from the proton.

K-MESONS, HYPERONS, AND OTHER PARTICLES

In recent years, as has already been mentioned, many other unstable particles have been discovered. First there are the K-mesons, which are more than three times as massive as the π-mesons; they, too, can be emitted by nucleons and can transmit interactions between pairs of nucleons. There are also the hyperons—particles which are heavier than nucleons and can be formed from nucleons in high-energy collisions. Just as a sufficiently high-energy π-meson can produce a nucleon-antinucleon pair, it can, if it has a somewhat greater energy, produce a hyperon-antihyperon pair. These will be able to exist at distances less than 0·1 fermi from the nucleon for a fleeting instant.

The proton is continually emitting and absorbing virtual K-mesons. When this happens, it becomes transformed temporarily into a hyperon (Fig. 7*f*), this action representing a much larger energy fluctuation than that needed for the emission of a π-meson. Using a similar argument to that outlined above, the K-mesons will be confined to within a radius of a few tenths of a fermi from the centre of the nucleon.

All these constituents of the cloud surrounding a proton arise from its interaction with meson fields. But the proton, by virtue of its electric charge, also interacts with the electromagnetic field. This causes the cloud to be augmented with photons, and electron and positron pairs (Figs. 7*g* and 7*h*). These may be found at much greater distances —out to 4×10^{-11} cm from the proton. To complete the picture, the much weaker interaction between the proton and the field responsible for the beta decay may very occasionally cause the emission of virtual electrons, positrons, and neutrinos, but these will be very

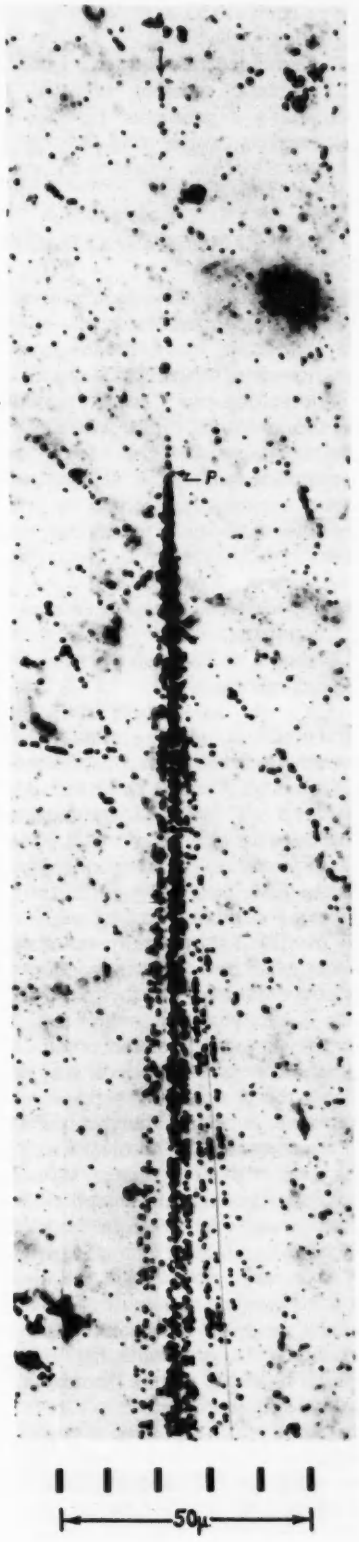


FIG. 8 (*right*). The tracks produced in a photographic emulsion by the collision of a high-energy cosmic-ray proton (300 MeV) with a stationary proton in the emulsion. A spray of twenty-eight mesons is ejected as a result of the collision.
(*From* "The Study of Elementary Particles by the Photographic Method" *by C. F. Powell, P. H. Fowler, and D. H. Perkins, by courtesy of Pergamon Press*)

rare in comparison with the remaining population of the cloud.

The extended distribution of charge and magnetic moment revealed by Hofstadter's experiments have to be interpreted as arising from the charges and currents of the π-mesons and other particles in the cloud.

ATTENTION FOCUSED ON PI-MESON

The picture of a nucleon presented here is so complex that it might appear to defy detailed study. At the present time, however, progress is being made in investigating phenomena associated with the π-mesons in the fringe of the cloud that are more than 1 fermi from the centre of the nucleon. These are of interest because high-energy incident π-mesons may make collisions with nucleons without passing closer than about 1 fermi. Such collisions may be taking place with a single π-meson of the cloud that is so far from the nucleon core as to be almost free. The incident π-meson may be deflected through a very small angle or the peripheral π-meson may be ejected, leaving the nucleon structure excited. Methods such as these provide the most practicable way of investigating the interaction between two π-mesons.

If a second nucleon is in collision with the first, it may capture one of the peripheral π-mesons and be scattered. It is possible to account quantitatively for many features of the interaction between two nucleons by such a process.

At higher energies, the collision processes are much more complicated since the core of one nucleon may pass through the cloud or even the core of the second nucleon. Many of the virtual π-mesons, K-mesons, nucleon pairs, etc., may be given sufficient kinetic energy in such a collision to escape from their parent nucleon, producing spectacular "stars" or sprays of fast-moving particles. Fig. 8 shows just such a spray of some twenty-eight particles produced by the collision of a very high energy cosmic-ray proton (3 million MeV) with a proton in a photographic emulsion.

In terms of the picture of nucleon structure outlined above, attempts have been made to calculate the expected form factors in terms of the interaction between the incident electrons and the charge and currents of π-mesons in the cloud, but there is still a great deal to be done before the measured distribution can be understood in this way. Interactions involving two or more mesons are important; the results depend on the interaction between mesons themselves, about which too little is known at present.

The calculations also involve the structure of the π-meson itself. As a result of such studies, it should eventually be possible to get information about the distribution of charge in the π-meson itself—the so-called π-meson form factor. The study of meson production in electron collisions may be particularly important in this respect.

In all of the work in which fast electrons are used as probes to explore nucleon structure, the implicit assumption is made that the electron interacts with the nucleon through the electromagnetic field only and according to the familiar laws of electromagnetism that hold for lower-energy phenomena and for greater distances of approach.

DO DISTANCE AND TIME HAVE A LOWER LIMIT?

It has often been conjectured that since some quantities such as angular momentum and energy are quantised, so distance and time might also be quantised. This would imply that motion would consist of a large number of sudden jumps through some fundamental minimum distance, while time would progress in a step-like process. If some such fundamental minimum distance should exist, one might expect to find a breakdown of the laws of electrodynamics at distances approaching this minimum. Such a breakdown could take the form, for instance, of the electron behaving like a sphere of finite radius instead of as a point charge. Or, alternatively, the inverse square law of interaction between charge might be modified to become proportional to $(r+\delta)^{-2}$ instead of r^{-2}, where δ is a small distance.

One most effective way to test such a possibility is to study collisions between pairs of electrons at very great energy. In this case the scattering should be determined by the laws of electrodynamics unobscured by nuclear properties. The experiment must be carried out at a very high energy of relative motion of the two electrons in order that they may approach closely enough to bring into evidence any breakdown of the laws of electrodynamics. If an incident beam of electrons is made to bombard the electrons in a stationary target, it is a peculiarity of relativistic kinematics that only a comparatively small fraction of the bombarding energy represents energy of relative motion. Most of it is energy of motion of the centre of mass of the whole system. For a beam of 1000 MeV electrons striking a stationary target, for example, the energy of relative motion is only 30 MeV. On the other hand, if two beams of 500 MeV are made to collide head on, the total energy of relative motion is only 30 MeV. An experiment is now being prepared at the Stanford linear accelerator in which two such beams of electrons are made to collide with each other. By studying the angular distribution of electrons scattered, particularly through a large angle (corresponding to very close collisions), any breakdown of the laws of electro-dynamics should be brought into evidence. If such a breakdown is found, some of the conclusions concerning the distribution of electric charge and magnetic movement in nucleons might need to be modified. The result would have tremendous inherent interest.

SUMMARY

We see, therefore, that the nucleon has, in fact, a structure that is quite complicated, but we also see that to interpret it we do not need to suppose that more fundamental, smaller entities exist. Indeed, owing to the possibility of the interaction of the nucleon with other nucleons and its relation to the large number of other unstable fundamental particles that have been discovered, the ideas of quantum field would require the existence of a cloud of finite extent of extremely complex structure around a nucleon. The experimentally observed extent and structure of protons and neutrons are consistent with that expected from this picture. The detailed study of nuclear structure is at a very early stage, however. Many points remain to be cleared up and the whole subject promises a large number of fascinating surprises in the future.

TEACHING MACHINES

JOHN ANNETT, HARRY KAY, and MAX SIME

The use of teaching machines may soon bring about a revolution in education, not only by making it more efficient but by bringing new insights into the little-understood process of learning itself. Machines have already been built that can adapt themselves to the individual student; it should be possible to develop units that can automatically learn from their students how best to teach various subjects.

"The Science of Learning and the Art of Teaching" was the title of a paper delivered by Prof. B. F. Skinner[3] of Harvard at a conference on "Psychology and the Behavioural Sciences" at Pittsburgh in 1954. It inaugurated what may become a revolution in educational techniques—the use of machines as effective instruments of education.

Skinner's theme was that principles of learning discovered in the psychological laboratories can be applied to everyday teaching, but only if a machine is used to relieve the teacher of the extra work this would involve. After more than half a century of research, however, there is still no general agreement on the principles or laws of learning, and Skinner's position is by no means shared by all psychologists, including the present authors. Other work suggests, furthermore, that it is not necessary to have a theory of learning in order to be able to design a good teaching machine; there are also indications that machines could be used to discover principles of learning. Current research on teaching machines, going well beyond Skinner's original conception, presents some interesting prospects for both psychology and education.

In America, the movement to "automate" teaching has grown rapidly since 1954 and now involves multi-million dollar investment in research and development by educational foundations, engineering industries, and government agencies. In Britain, with the peak of the birth-rate bulge on the point of stretching industrial and technical training facilities to the limits and, indeed, a general shortage of teachers of all kinds, there could hardly be a more appropriate time to consider the possibilities of teaching machines.

The authors are members of a research team that is investigating training problems and, in particular, the possibilities of teaching machines. This research is being financed by the Department of Scientific and Industrial Research.

Dr Annett has done research on human learning and industrial training and has made a first-hand study of the teaching machine movement in the U.S.A.

Professor Kay, the first occupant of the Chair in Psychology at Sheffield University, has worked on human learning and performance, and ageing.

Mr Sime has worked on calculating machines, and animal and human learning.

FROM THE LABORATORY TO THE CLASSROOM

There is nothing particularly new or revolutionary about mechanical aids to teaching. The U.S. Patent Office records over 600 teaching devices invented between 1809 and 1960. The modern teacher makes use of devices ranging from coloured sticks and flash cards to tape recorders and closed circuit television. A significant feature of recent developments is that they have come, in the main, from experimental psychology rather than from education. The study of learning has occupied psychologists since the latter part of the 19th century, but the experimentalist, in search of simplification, has had more to say about rats and nonsense syllables than about children and school curricula. There have been some notable exceptions, of course. E. L. Thorndike, one of the founders of modern learning theory, was an educationalist who sought to apply laboratory results to educational practice. He formulated several laws of learning, one of which—the law of effect—has become the basis of several learning theories, including Skinner's.

In general terms, the law of effect states that learning occurs if a response to a given situation is followed by some effect which is rewarding for the learner. The response is then said to be reinforced and the reward is sometimes known as reinforcement. As originally formulated, a punishing effect would give the reverse results, but interest now centres mainly on reward or reinforcement.

S. L. Pressey in 1926 found what appeared to be a useful example of the law of effect in an attempt to test students' achievement with a simple scoring device. They were given a set of questions, each with several possible answers of which only one was correct. For each question, there was a set of holes punched in a board and the students registered their answers by pushing a stylus into the hole corresponding to the answer they wished to choose. A concealed template allowed the stylus to pass through if the right answer was chosen but blocked all others so that the student immediately knew if his answer was right. Pressey found that this device and others like it not only tested achievement but also helped students to learn. Each response had an immediate effect and it was presumed that this was in some way rewarding when the responses were correct. Pressey's work really marked the beginning of the teaching machine movement, although it was not publicised much at the time. Even a device as simple as Pressey's is not merely a method of presenting examples or information; it actually does an important part of the teaching itself. It is a true teaching machine and not simply a teaching aid.

Skinner's work centres round the effect of reward; the most important way in which it differs from Thorndike's work is in an improved experimental technique. Reward or reinforcement cannot help until the right response has in fact occurred. Skinner's technique ensures that the right response will occur, as an example will show. Instead of a complicated puzzle box or a maze, Skinner places an experimental animal in a simple box that usually has a lever which the animal can press to get a reward of food. There is little else, indeed, the animal can do except preen

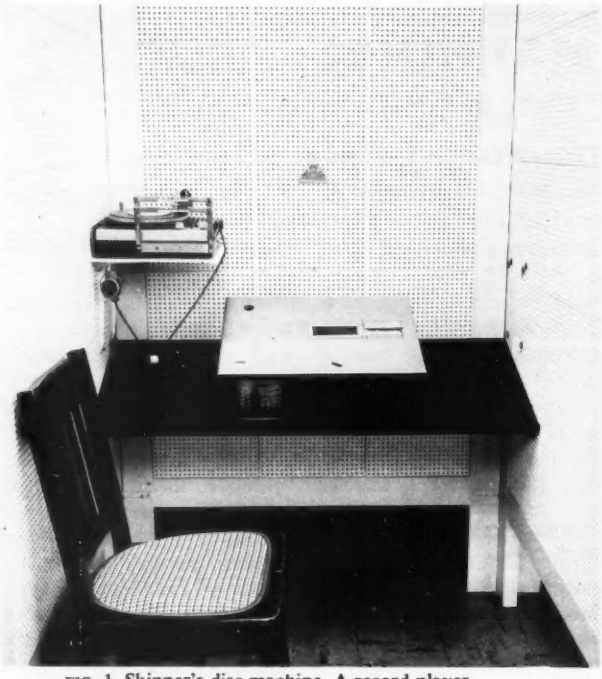


FIG. 1. Skinner's disc machine. A record player has been added for auditory presentations.
(Harvard University)

FIG. 2. Drs Lumsdaine (*seated*) and Glaser of the University of Pittsburgh with (*left to right*) the Atronic Learning System (a multiple choice device), the Foringer Teaching Machine (constructed response), and a programmed textbook.
(Carl Purcell, National Education Association, U.S.A.)

itself or go to sleep, and so the simple response is soon learned. If we want to teach a more complex response, it must be built up or "shaped" by teaching first a number of simple component responses. For example, a pigeon can be taught to walk a figure-of-eight by first being given a reward when it makes any turning movement. Later, when turning is well established, the reward is made contingent on changing direction and very soon a full figure-of-eight is established.

These factors of simplification, reward, and gradual shaping of complex responses are the essentials of his experimental technique and of the teaching machines he has devised. Skinner is convinced (as many other psychologists are not) that telling a student his answer is right is a sufficient reward and is, in a sense, comparable to the animal receiving food on making the right response. In a human the reward value of being right is derived from long experience. It is a secondary rather than primary reinforcement but, Skinner contends, essentially the same in its effects. Even in a highly congenial classroom rewards are less frequent than in the laboratory. In a classroom, particularly a large one, the teacher has no time to check the details of an individual's performance. Skinner's answer to these problems follows from his experimental technique; the use of a machine becomes necessary for reasons of economy. By analogy the subject matter to be learned has to be broken down into small steps which will be components of the ultimately desired complex responses. These steps look like very simple questions and often are statements which call for the insertion of missing words. When a student answers the "question" correctly he has, by analogy, made a response which is part of the total behaviour to be learned and he is then rewarded by the information that he is correct. Normally a teacher would think it odd to ask only questions which he expected to be answered correctly, but to approximate this situation is, according to Skinner, of the greatest importance.

Skinner and his colleagues have built several machines with the purpose of giving individual students step-by-step reinforcement. One which can teach most kinds of academic subject-matter, given a suitable programme, is shown in Fig. 1. A programme of subject-matter is printed radially on a disc and the student sees one item of information at a time through a small slot. Each item requires completion, which is always easy, and the student writes his answer on a paper roll seen through a second slot. He then presses a lever which reveals the correct answer at the same time covering his own answer with a transparent shutter so that it cannot be altered. He then scores himself right or wrong by moving the lever and another item is presented. The disc continues to rotate at the student's own pace through some thirty items and on the second time round skips over the items which have been scored correct, and so until every question has been understood, answered correctly and "reinforced". A significant characteristic of this machine is that the student cannot progress until he has mastered previous subject-matter and the machine repeats the bits he finds diffi-

FIG. 3. The AutoTutor. Student is confronted with a multiple-choice question and uses the keyboard to select his answer. If the answer is correct, the machine automatically goes on to the next part of the lesson. If the answer is wrong, the machine presents an explanation or a sequence of correctional material and then goes back to the original question.
(U.S. Industries Inc. Ltd.)

cult. According to Skinner, all students in this way learn everything they are supposed to know without gaps and, of course, without the aid of an individual tutor. The bright student can go ahead rapidly; the dull student takes longer but gets there in the end. On the average, the time taken is less than by traditional methods since time is used more efficiently.

However important a device may be in performing the hard labour of frequent and immediate reinforcement, a quick look at some programmed material will show that a great deal of extra, but perhaps more fruitful, labour is required of the teacher. Samples of programmed material are shown on the following two pages. The total response is built up from a series of small steps based on a detailed analysis of the subject-matter by a competent teacher and later modified as the result of the pupils' actual learning.

Within the framework of Skinner's original idea, Glaser, Homme, and Evans[1] have devised a simple but effective teaching "machine", a programme of small steps in book form (*see* Fig. 2). A Programmed Textbook differs from an ordinary textbook by presenting the subject-matter in small logical steps, giving an item of information and asking a question which the student should (and in fact usually does) answer correctly; by turning the page the answer is confirmed. In this way, a complex concept is built up step by step. This new way of writing textbooks has already been taken up by educational publishers; programmes on a variety of subjects including maths and statistics, English and languages are now available. A multiple choice device is seen in Fig. 3.

An obvious virtue of the programmed text (as of the Skinner type teaching machines) is that the student is required to read the text in an efficient way, progressing to new information only when preceding steps have been understood.

There is little doubt that a teaching machine containing a good programme, is capable of teaching effectively. What is less sure is that the system works for the reason given by its designer. There is no general agreement amongst psychologists on the principle of reinforcement and the validity of the analogy between animal and human learning. Moreover, there is good reason to suppose that it is not necessary to have any principles or laws of learning before being able to build a satisfactory teaching machine. Skinner's machines do two things which are not directly dependent on any particular theory of learning but which virtually guarantee success. First, the subject-matter to be taught must be presented simply, clearly and logically. This means that the teacher must seriously consider and anticipate the difficulties of the student. Second, a machine, because it is operated by the student, only passes on information when he is paying attention. The basic requirements for learning are inherent in this situation for it essentially brings the thoughts of the teacher and the thoughts of the student closer together, despite the hardware which intervenes between them. Just how and why learning occurs is quite another matter.

CYBERNETICS AND INDIVIDUAL TUITION

Skinner's ideas, put most strikingly into practice, are as stimulating as they are controversial; a number of teachers, psychologists, and engineers have produced their own analyses of the teaching–learning situation and their own devices to cope with the problems they encounter.

Cyberneticians over the past ten years have developed a number of self-adjusting mechanisms which are capable of learning from experience. An important step has been made by Pask who showed that such a mechanism can not only learn but can also teach. The cybernetic approach to teaching machines avoids the problems of learning theory and simply attempts to mimic the process of individual tuition. For a machine to behave in this way, it also requires a primitive ability to learn.

The work of N. A. Crowder, a psychologist, illustrates this approach most simply. In a conventional lecture, the material to be learned is presented to all of the students in one way, irrespective of their individual differences and whether or not they happen to be paying attention at the time. Subsequent homework and tests, often hours and sometimes months after the original instruction, show up deficiences in

SPELLING

1. The letters a, e, i, o, u are vowels. Cat has the vowel a. Pet has the vow__ e.

el	

2. There is at least one vowel in every word. Bat has the___ el a.

vow	

3. The letters a, e, i, o, u are vow__s.

el	

4. Hot has the vowel o. Hit has the vowel i. Hat has the vowel__.

a	

5. The letters a, e, i, o, u are_____s.

vowel	

6. The letters__, e, i, o, u are vowels.

a	

7. The word let has the vo___ e.

wel	

8. Top has the vowel o, and set has the vowel__.

e	

9. The letters__,__, i, o, u are vowels.

a, e	

10. The word hot has the vowel__, and the word hit has the vowel__.

o, i	

11. A _____ is a road across a river. (bridge)

bridge	

12. In bridge there is an (what letter?) __between the r and d?

i	

13. The last 3 letters of bridge are___.

dge	

This spelling course designed by TMI-Grolier consists of 3000 frames and requires that the student spell 400 complete words and significant parts of a few hundred more. The programme begins by teaching vowel-consonant discrimination with emphasis on vowel sounds and covers a number of familiar spelling rules. The most difficult words in this course are words like television, consonant, and photograph. The minimum time for completion has been found to be fifteen hours.

BASIC RUSSIAN

1. The Russian sound: spaSEEbo* ← (These mean COPY the words).
Means: thanks* ←
(Capital letters show accented syllables.)

spaSEEbo thanks	Russian sound: Means:

2. Russian sound: spaSEEbo
Means: ____* ← (This means fill in what is missing.)

thanks	

3. The "a" in "spaSEEbo" is sounded "ah," like the "a" in "father." Therefore, the "a" in "spaSEEbo" and "father" is sounded ____* ← (Fill in pronunciation.)

ah	

4. Russian sound: spaSEE____* ← (Fill in what is missing.)
Means: thanks

bo	Russian sound: spaSEE__

5. The "o" in "spaSEEbo" is sounded somewhat like the "aw" in "crawl." Therefore, "bo" is sounded ____*

baw	

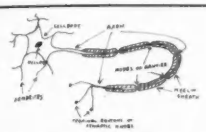
6. The "a" in "spaSEEbo" sounds like the ____* in "father."
The "o" in "spaSEEbo" sounds like the ____* in "bawl."

a, aw	

This Russian course by TMI-Grolier requires about eighteen to twenty hours to complete and has been tested on students as young as twelve years of age. It is designed to teach the Cyrillic alphabet, recognition of over 100 cognates and active use of over 100 words, use of at least thirty-five phrases, counting, the telling of time, conjugations of verbs, tenses, and the use of possessive pronouns. The assistance of a teacher for pronunciation is recommended for the beginning student; pronunciation guides are intended for U.S. students.

Right, the TMI-Grolier machine. The correct answer can only be seen when the pupil has written his in the space provided and moved the paper up under a transparent screen that prevents him from changing his answer.

THE CONDUCTION OF THE NERVOUS IMPULSE

FRONT OF CARD	BACK
1. The basic unit of which the nervous system is composed is the NERVE CELL or NEURONE. Hence we say that the brain and nervous system are made up of large numbers of_____.	nerve cells or neurones
2. Now make a copy of Picture 1, and put it on one side where you can see it.	
3. 	
4. The body of the cell contains the_____.	nucleus
5. From the body of the cell several processes stick out. 1. The single long one is called an _____. 2. The short ones are called _____.	axon dendrites
6. The axon, which is the_____-est of the processes which leave the cell body, is covered by the _____ sheath.	longest myelin
7. The myelin_____is made of fatty material, and is interrupted every few millimetres by the _____ of _____.	sheath Nodes of Ranvier
8. The axon finished by dividing into fine fibres which end in _____ _____ or synaptic knobs.	terminal boutons
9. The name "synaptic knob" is another name for the _____ _____.	terminal boutons
10. The terminal boutons (or_____ _____) make contact with the cell_____of another neurone but not with its dendrites or axon.	synaptic knobs body
11. Now turn your copy of Picture 1, over or cover it so that you cannot see it any more.	
12. Make a copy of Picture 2.	

This programme was designed by the authors in consultation with Dr N. Moray, an expert in the subject matter, for an introductory course on psychology for university students. Now on 3 in. × 5 in. cards, it can readily be placed into a machine. The student is required to write down his answer before looking at the back of the card.

STATISTICS

FRONT OF CARD	BACK
1. The formula for the STANDARD DEVIATION of a set of scores is $\sigma=\sqrt{\frac{\Sigma x^2}{N}}$ Copy it. Check your copy and keep it in front of you	$\sigma=\sqrt{\frac{\Sigma x^2}{N}}$
2. $2=\sqrt{4}$ and $2^2=4$ So if $a=\sqrt{b}$ $a^2=$ _____ and if $X=\sqrt{Y}$ _____ $= Y$	$a^2=b$ $x^2=Y$
3. $\sigma=\sqrt{\frac{\Sigma x^2}{N}}$ This formula should look familiar. It is the formula for the _____. Now complete this formula $\sigma^2=$ _____ and this $=\frac{\Sigma x^2}{N}$	Standard deviation $\frac{\Sigma x^2}{N}$ σ^2
4. $\sigma^2=\frac{\Sigma x^2}{N}$ is the formula you have just arrived at by_____ing both sides of the formula for the Standard deviation. Copy it, check it, keep it handy	Squaring
5. $\sigma^2=\frac{\Sigma x^2}{N}$ is the formula for the VARIANCE. You get it by squaring the _____	Standard deviation
6. Write out the formulae for the Standard deviation and the variance without looking at your copies	$\sigma=\sqrt{\frac{\Sigma x^2}{N}}$ $\sigma^2=\frac{\Sigma x^2}{N}$
7. Let's look at the VARIANCE. Write down the top line of the right-hand side of the equation	Σx^2
8. Σ is a Greek letter, pronounced sigma, which means the sum of whatever is written to the right of it. Σx means _____ Σx^2 means _____	The sum of all the xs The sum of all the x^2s If you got this wrong pay very close attention to the next card
9. Σx means _____ Σx^2 means _____ So x and x^2 are symbols representing a whole class of numbers and_____tells you they have to be added up	The sum of all the xs The sum of all the x^2s Σ

This programme was designed by the authors for first-year undergraduates in psychology who do not have a mathematical background.

understanding but this is too late. The educational engine grinds on inexorably, beyond control by the individual student who may be left for ever trailing miserably behind.

In order to reproduce the individual tuition situation, material must be introduced according to the student's progress, and testing must be immediate to give confirmation or re-route the student through additional explanations and exercises. Further progress must be contingent on mastering basic principles. On the basis of one pupil—one teacher, this method is quite possible but in modern conditions the expense would be prohibitive even if the supply of trained teachers were adequate.

However, a device which presents material only when the student is paying attention, and which immediately tests his understanding and re-routes him to further explanation if necessary, fulfills some of the essential functions of a tutor. It is a fascinating paradox that a teaching machine constructed on this principle is far more flexible, far more individual, and in a sense far *less mechanised* than the mass-production methods of a human teacher with a large class and a syllabus to get through at all costs before the end of term. Such a machine has been built and is now commercially available although it is fairly expensive. The cost is about the same as that of training a human teacher but it can teach more students without getting tired which, for a first attempt at establishing the principle, is quite an achievement. There is little doubt that with increased demand and engineering improvements, future machines will be economically feasible. We in our department are currently working on an improved design which we hope may be produced cheaply.

MACHINES TO TEACH LEARNING THEORISTS

From the scientists point of view teaching machines are of great interest not simply because of their potential benefits to education, which has not seen individual tuition on any scale for centuries, but also because they offer the unexpected possibility of carrying out accurately controlled learning experiments in a real life situation and may stimulate theories and models of learning.

An ideal teaching machine could embody laws of learning in rather the same way that the hierarchy of control mechanisms in a ship are an embodiment of fixed physical laws designed to meet the contingencies of any voyage. The journey from ignorance to knowledge of an individual student may remain a unique series of events whilst being controlled by a set of fixed rules. A satisfactory set of rules has yet to be drawn up, but the experimental use of teaching machines is one route by which rules or laws of learning could emerge.

Skinner has entered the field suggesting one basic rule—the principle of reinforcement—and a Skinner-type programme is designed to maximise the effectiveness of this rule. But, in principle, a machine could enter the field with no fixed rules and develop its own, *provided it had some means of learning from its students.* This ideal machine's principle attribute would be that it could itself learn. This ability to learn from the student is a characteristic of good teachers, either human or mechanical.

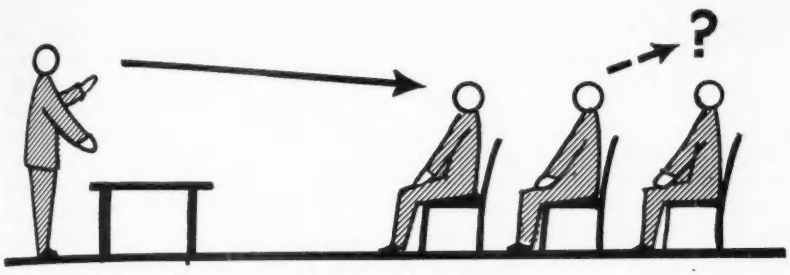
Existing teaching machines learn from their students in varying degrees. A Skinner-type programme "learns" only by being rewritten in accordance with the success or failure of past students. A programme on introductory psychology in use at Harvard is undergoing regular revisions according to the rule that reinforcement should be maximised. This is done by rewriting items on which mistakes are made so that only a few errors are made by an average student in an entire programme. A Crowder-type programme adapts itself to each individual student and has built-in rules about the additional information and explanation to be provided for any given error. The programming is "intrinsic" to the machine, once all the relevant information has been set down. It is therefore desirable that as many contingencies should be prepared for as possible and this is partly why a machine built on Crowder's principle of "intrinsic programming" is expensive. A more sophisticated machine could be designed which did take account of the actual frequency of various contingencies; such a unit would gradually eliminate redundant subject-matter from its store and call for help when new contingencies arose that were not predicted by the programme writer. If this design were not an economic proposition for general classroom use, it would at least teach us how to write optimal programmes and would have enormous value in constructing suitable syllabuses which could then be presented by means involving less capital outlay, such as programmed textbooks.

SAKI

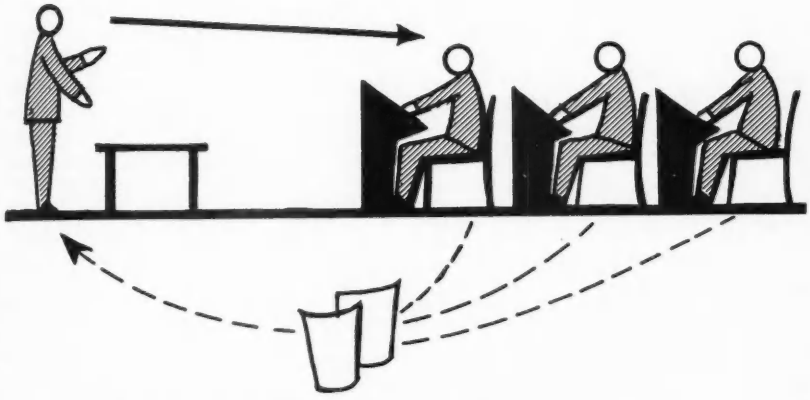
Perhaps the most sophisticated teaching-learning machine at present in use is Saki, designed by Pask[2] in collaboration with Solartron Electronics, to train punch-card keyboard operators. The machine adapts to the student according to a limited set of rules. The correct keys are clearly indicated if the trainee is inclined to make errors and if difficulty is experienced with any particular symbol it will appear more often. The presentation rate speeds up automatically as the trainee becomes more expert and this can develop into a kind of race between the trainee and the machine. The essence of this type of teaching machine is that it builds up inside itself a model of the individual trainee representing his specific difficulties, in much the same way that a human teacher, by getting to know a pupil, will appreciate his difficulties. However, a weakness of this type of machine is that the techniques and strategies it adopts to cope with difficulties depend on the commonsense or insight of the designer rather than being determined by a theory of learning. This criticism is relatively minor in view of the lack of a set of well-established principles of learning. Saki's programming is intrinsic in the sense that it contains feedback loops whereby the machine adapts to the trainee as the trainee does to the machine, but the number and nature of these feedback loops must still be determined extrinsically by the designer. Although more sophisticated types of machine may never come into general use, they certainly can provide some helpful insights into the teaching-learning process.

TWO-WAY COMMUNICATION

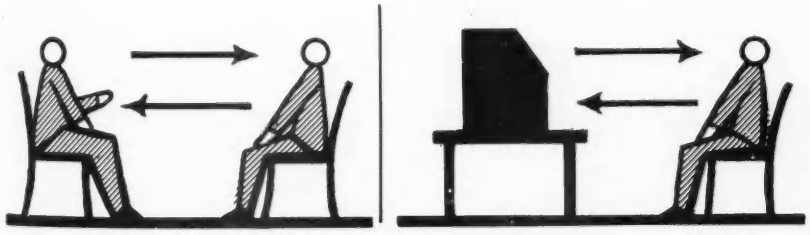
Whilst one would hesitate to reduce teaching to a branch of cybernetics, these machines underline the central



With lectures, films, or television presentations, there is no feedback to the teacher.



With occasional examinations, there is some feedback but it is often too late to help in controlling the learning.



With individual tuition or a teaching machine, there is immediate feedback and learning is well under control. Teacher (or machine) and student are in continuous and constructive communication.

FIG. 4.

importance of feedback and demonstrate how this essential feature is missing from mass media such as lectures, films, and television. Feedback, as can be seen in Fig. 4, may operate in several ways. In a lecture, film, television or even textbook presentation, the effect of the material on the student is virtually uncontrolled since there is no immediate feedback from the student. If tests or examinations are introduced, some element of control can be exerted by the student on the subject-matter and the way it is presented, but the longer the delay the less effective the control. In short, the very worst time to hold an examination is at the end of the course when neither teacher nor student may benefit and only mutual hostility flourishes. In individual tuition, which some teaching machines attempt to mimic, the feedback control is direct. The teacher modifies the student and the student modifies the teacher by feeding back information about his difficulties, which should cause the teacher to revise his subject-matter presentation. Teaching machines should not, therefore, be regarded simply as a new method for teaching but as a technique for effectively applying methods which are already partly known, and for validating these and new methods which might emerge. The implications for educational research are at least as great as those for practical teaching.

THE VALUE OF MACHINES

By placing teaching machines in the class of self-correcting systems, at least in principle, it could be argued that their validity as means of education is not open to question. Such a fine point, however, will not deter many people from asking simply "Do they work?" and "Are they better than traditional methods?" A great deal of research is under way to answer these questions.

Preliminary results with machines and programmes have been good. In one case study time was used so effectively, a whole year's work in mathematics was covered in one term. As predicted, students find the programmes easy to work with and learning blocks become less frequent. The ease of learning with a programmed machine may make some teachers sceptical over the question of retention but there is no evidence so far which indicates that material which is learned quickly and easily is forgotten quickly and easily; indeed, learning theory suggests that the reverse is to be expected. It has been shown that one of the most potent causes of "forgetting" is that the material was misunderstood in the first place; a good programme goes a long way to removing this difficulty.

It is too early to reach any conclusion

on long-term retention, however, as few programmes have been in existence long enough for long-term effects to be measured. There is another unknown factor: students have generally gone through the material covered in the programmes much more rapidly than they would by normal procedures; if such programmes were used with greater time intervals between lessons, revision items might be inadequate. Whilst there is no evidence that this does happen, it seems to be a point worth careful consideration when trying to integrate programmed instruction into the usual school curriculum.

Preliminary results leave no doubt that machines can teach effectively, but the question of the possible superiority over human teachers is difficult to answer. Since no truly self-programming device has yet been built and tested *existing machines are as good as the programmes they present and these are only as good as human teachers can make them.* A good teacher will probably be able to write a better programme than a bad teacher until more is found out about optimal programming. A more rational question to ask at this stage is where and how the facilities offered by machine teaching can be used to overcome our present and anticipated educational problems.

It seems probable that teaching machines will prove most useful in a combination of the following conditions:

(i) Where there is a shortage of human teachers.
(ii) Where individuals or small groups of students are physically isolated from qualified teachers dealing with some special subject.
(iii) Where the subject-matter and the end result can be most closely specified and put in an appropriate form.
(iv) In subjects where drill and routine practice would benefit from accurate monitoring.
(v) Where the pupil requires more attention and patience than a human teacher can reasonably be expected to give.

Under such conditions most technical and scientific subjects would benefit from machine teaching up to an intermediate level, giving students a sound basis on which the teacher can later build. Some aspects of language teaching, grammar, and vocabulary and spelling are obvious candidates. Motor skills, which quite often already involve the use of expensive apparatus and simulators, could be machine taught; in fact, the teaching machine could be an integral part of the equipment. Some problems of remedial education, particularly where retardation is partly a social adjustment problem, offer an interesting challenge to machine designers. At this stage it would seem both unwise and unrealistic to programme subjects like art appreciation or citizenship, although teaching-machine enthusiasts are able to convince themselves that it could in principle be done.

TEACHING MACHINES AND COMMUNICATION DEVELOPMENTS

Teaching machines are the product of an age concerned as never before with the communication of information, and are part of an attempt to deal with one of the most crucial and difficult of all communication problems. Engineers have made such great advances in the transmission of information between separate points in space and time that we may be apt to forget that in most cases the purpose of a communication channel is to get information from one human being to another. As more and more scientific and other information is generated and as the capacity of physical channels to transmit or store it is multiplied, so the problem of actually getting it out of one human being and into another grows and the existence of a bottleneck becomes more obvious. Teaching machines are a logical development in this crucial element of human communication and the introduction of automated teaching will surely contribute to the solution of some of these problems.

The feature which all the machines we have described (whether electronic, mechanical, paper and pencil or human) have in common is a two-way flow of information. The flow of information from the student back to the teacher is essential to the flow of information from the teacher to the student.

The bits and pieces of which this two-way communication system (or teaching machine) is made up are not in themselves very important and may be determined by the kind of material being taught or by economic considerations. In many cases a human teacher is, and will remain, an essential element in the system, but the usefulness of human teachers is too often limited by their inadequate numbers. Further, some machines, such as Saki, might do better than a human teacher, having much the same advantage as an "electronic idiot" has over a trained mathematician; that is, it can do things faster and more accurately, provided it has a programme which tells it exactly what to do.

The main distinction to be made between types of existing teaching-machine designs is between systems such as Skinner's, which incorporate principles of learning, and those like Crowder's, which emphasise the two-way communication system without any deliberate attempt to incorporate formal rules. The hypothetical ideal teaching machine we have outlined would incorporate a comprehensive two-way communication system and either a set of established teaching rules or a system for discovering rules. That is, it would learn not only what the student's difficulties were but what methods were effective in dealing with them. Such a machine or system already exists in a sense, for it combines the functions of the teacher and the learning theorist. Education and experimental psychology are indeed loosely connected elements in a system for dealing with human communication problems and it is not unreasonable to suppose that the system might be more effective with a closer co-operation between its elements.

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THE REGROUPING OF SEPARATED CELLS

A. S. G. CURTIS

How do the cells forming in an embryo move to the right place? Why do normal cells in an adult animal stay in the correct place whilst tumours spread through the body? Why do small wounds heal properly whilst large ones develop scar tissue? Some light is thrown on these questions by the examination of a versatile experimental system.

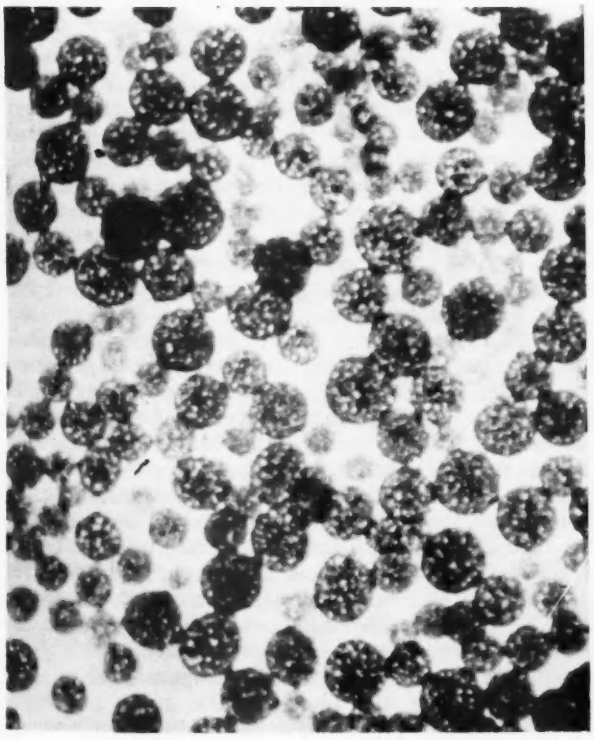
Why do the cells of an adult animal for the most part stay roughly in the same place so that the anatomy of the body remains constant and correct? At first this may seem a slightly naïve question, but once we consider two related questions its importance becomes clearer.

When an animal develops, there is a considerable movement of cells from one or other parts of the embryo to the final positions they will occupy in the adult. How are the cells directed to the correct place? Likewise, when a tumour starts to spread through the body, what has happened to prevent the cells staying in their normal and correct place? All these questions indicate that some precise process—a specificity—is involved in deciding where a cell places itself in the body.

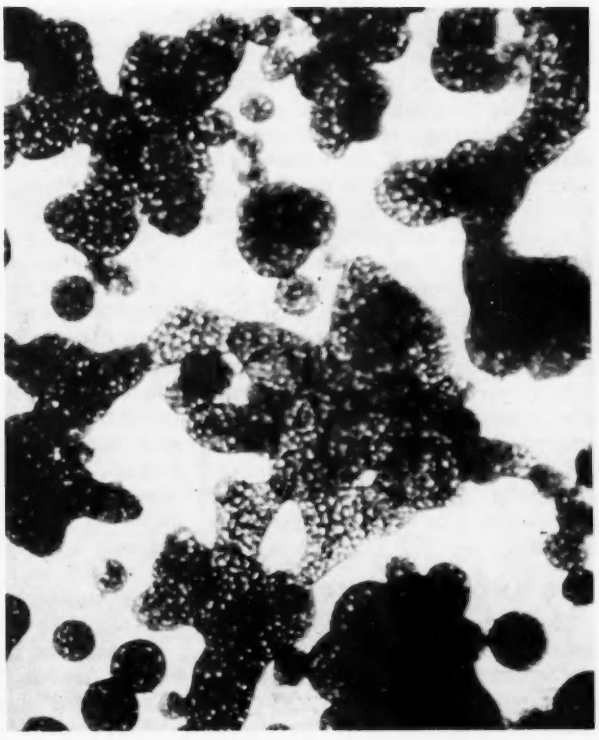
The process of *reaggregation* is a most striking display of such a specificity, and its study suggests some answers to these questions. If a simple animal like a sponge or sea-anemone, or a more complex one such as an embryo of a bird or amphibian, is squeezed through a fine net or placed in a solution free of calcium or magnesium ions, the cells of the animal separate. This process is called *disaggregation* or *dissociation*, and the cells settle slowly on to the bottom of the dish in which this has been done. Once calcium or magnesium is added to the medium, however, the cells begin to crawl around on the bottom of the dish. If they were initially fairly close to one another, they will frequently collide. When this happens they tend to stick to one another, forming groups of two cells, then three, four, and so on. By this means large bodies of adherent cells may be built

The research described here is part of a project at the Department of Anatomy and Embryology, University College, London. The project is being supported by the U.S. Public Health Service.

FIG. 1. A. Disaggregated cells of a toad embryo before any reaggregation has taken place. The larger cells are about 0·05 mm. in diameter and are filled with yolk granules.



B. The same cells some six hours later. They have grouped and adhered to form seven or so small reaggregates. With a higher density of cell population, one single reaggregate would form.



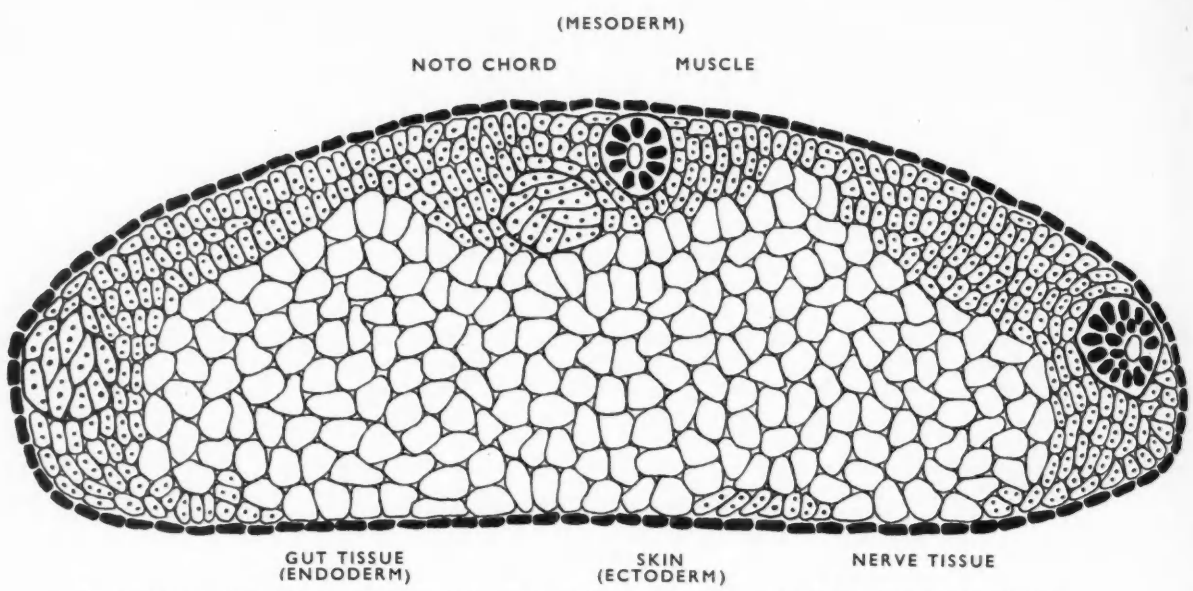


FIG. 2. Ideal section through a toad reaggregate some sixteen hours after reaggregation started, showing how the cells have sorted out to give a roughly concentric arrangement of ectoderm (heavy black) which is skin and nerve, mesoderm (dots) which comprises muscle and notochord (the precursor of the spine), and endoderm (cells without markings) which give rise to the gut tissue, etc.

up in the course of five to ten hours. This is the first stage of the phenomenon of reaggragation (*see* Fig. 1). So far, this process has not been achieved with cells from normal adult vertebrates, though some tumour cells are suspected of doing it naturally at phases of their spread through the body. Slime mould cells (a form of Protozoa) undergo reaggregation naturally during their life cycle.

The next stage of reaggregation is most remarkable. If the various cells have been well mixed in the disaggregate so that skin, nerve, muscle, cartilage cells, etc., are randomly placed, a sorting-out process operates which brings the various cell types to their correct place in the body or at least roughly so (*see* Fig. 2). In sponges, this sorting out is so successful that the rebuilt sponges can continue a normal life thereafter. In chick or toad embryos, however, the reaggregates do not form proper mouths and guts, and apparently die of starvation when their yolk (which acts as a food reserve) is exhausted.

SORTING OUT THE CELLS

This sorting-out process involves at least two forms of specificity: (1) a mechanism to ensure that like types of cell group together, and (2) a mechanism which determines that the various

FIG. 3. The sorting-out of cell types: the arrangement shown in (*a*) is never found; the tissues sort out concentrically as in (*b*).

types are roughly in the right place (*see* Fig. 3), although a mechanism achieving the latter would, of course, produce the first result. Basically, the cell types that are involved sort out concentrically, although subsequent movements of the cells may result in in-tuckings of various cell layers.

A third type of specificity also exists, operating at least in some situations—if two species of sponges are disaggregated and their cells intermingled, the cells of each species will separate out during the reaggregation. This happens with species of newt as well, though it does not apparently happen with mixtures of mouse and chick cells, as shown by Moscona;[5] he found there was only a recognition of tissue type and position so that complex "chick/mouse" muscles, cartilage, kidneys, etc., resulted.

What are the natures of these specificities? Are the final positions of the cells brought about by their moving randomly round inside the reaggregate and suddenly sticking down firmly when they reach their correct position? Or do they do it by moving in a direct and definite path to their correct position and just ceasing to move when they reach it? In other words, is it their movement or their adhesion which is specific, or is it both? This problem has never been properly investigated in any reaggregate, chiefly because their opacity makes it very difficult to follow any cell. By using time-lapse photography, however, Lucey and I[4] have shown that there is no directed movement or adhesion during the early stages of reaggregation. Of course it is obvious that movement and adhesion are most closely bound up because a cell must have a certain degree of adhesiveness in order to move. Without some adhesion the cell would merely slip; with too much it would fail to move.

The situation is quite different from that found in slime mould reaggregation, where the cells move towards

certain other cells by following a path towards higher concentrations of a chemical given out by these other cells (chemotaxis). But despite the possibility of chemotaxis explaining the type of sorting out being discussed here, it has been more usual to invoke explanations involving control through the specific adhesion of cells to those of like type alone.

SPECIFIC ADHESION

One way in which two cells might stick together is by chemical groupings bonding one cell to another. If these bonds were highly specific like those between an antibody and an antigen, cells of one type might adhere only to those of like type. Spiegel attempted to test this by preparing antibodies to sponge cells. When the antibody was added to sponge cells which were about to reaggregate, their reaggregation was prevented. The antibodies presumably combined with antigenic groups on the cell surface, making them no longer available for combination with other cells. But the antibody also stopped cell movement. Lack of movement would prevent reaggregation and thus the antibody may have had no effect on adhesiveness or none at least on any specific adhesion. This theory runs into a number of other difficulties:

1. As well as the possibility of specific adhesion, there is undoubtedly a degree of non-specific adhesiveness shown by most cells, so that at least one additional mechanism of adhesion must be postulated.

2. Divalent ions, such as calcium and magnesium, must be present if reaggregation is to occur, but are not usually essential for the reaction of antibody with antigen.

3. Although blood cells may be easily bound together with antibodies under experimental conditions, the bonds formed are so strong that it is impossible to separate the cells under any reasonable mechanical force, whereas cell adhesions are easily broken under the mild mechanical forces that cells can themselves exert. Of course, it is possible to explain this by assuming that very few antigen-antibody bonds form between cells naturally so that the adhesions are not very strong.

4. It is hard to explain how the cell types take up definite positions in the reaggregate.

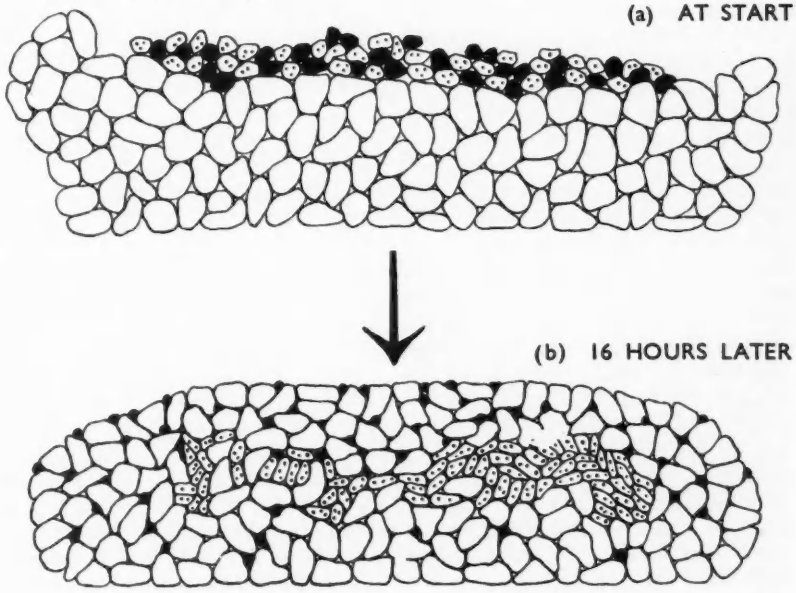
Another type of explanation of specific adhesion is that given by Steinberg,[6] who pictures all cells as bearing chemical groups on their surfaces which are capable of binding calcium atoms. Since calcium atoms can bind to two univalent groups, they might be caught on one side by a group from one cell surface and on the other side from another cell surface, forming a link that tends to bind the surfaces together. He suggests that each cell type bears a specific pattern of such groups which bind calcium. Most bonds would be formed between identical patterns (that is, between like cells), which would thus adhere most strongly, but some cross-links would form between all types of cell. This explains the existence of a non-specific adhesiveness, but requires that the cell surface be remarkably rigid so that the pattern can survive the stretchings and distortions caused by movement or changes in shape of the cell. In this theory and that previously mentioned, the specificity is pictured as being like that of printed words on a page—that is, a specific pattern on an area.

TEMPORAL SPECIFICITY

But there is another form of specificity—that in time. For example, the electrical impulses of a telephone message form such a pattern. In view of the defects of the theories of areal specificity, it seemed worth while to me to test whether any form of specificity in time controls the sorting-out process. The experiment to test this was very simple in essence. Cells of one type were started reaggregating some hours before a second. When the second type was added, it was not mixed with the first type but placed on top of it or inside it. An intermingling of the two cell types to form composite tissues would have been an indication that the specificity which controls the separation of differing tissues had been interfered with by altering the timing.

This result was found[1] with amphibian embryonic tissues (*see* Fig. 4). In this and other experiments using varying time delays it was possible to confuse the positioning process as well, so that skin was found inwards of gut tissue (*see* Fig. 5). These experiments are strong evidence that both the sorting-out and the positioning process are controlled by one and the same mechanism.

FIG. 4. The experiment to reveal the existence of a temporal specificity. Endoderm cells (no markings) are reaggregated for four hours before freshly disaggregated ectoderm (solid black) and mesoderm (dots) are placed on top (*a*). Sixteen hours later (*b*), the ectoderm and endoderm have intermingled, and the mesoderm has moved inside the endoderm. Interference with the timing of reaggregation has upset both the sorting-out and the positioning of the cell types.



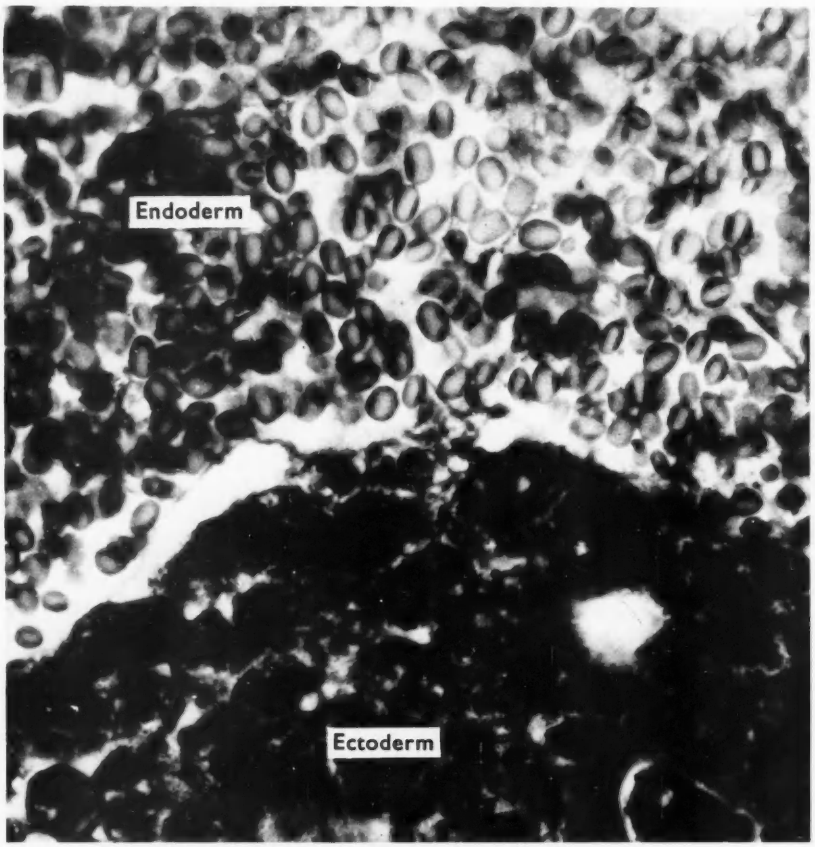


FIG. 5. A similar experiment to that shown in Fig. 4. Endoderm cells were reaggregated for six hours before ectoderm cells were placed on top. Sixteen hours later, as can be seen in this section, the ectoderm cells have positioned themselves as a dark pigmented mass inside the endoderm which is full of large oval yolk granules.

It is now evident that the sorting-out process normally works by some change taking place first in one cell type, bringing it to its right position, then in a second, and lastly in a third. Since confusing the timing affects the positioning of two or more cell types, the change must be of similar nature in each type. Further experiments like those just described indicated that the first type to alter its properties is the ectoderm, which gives rise to skin and nerves. The mesoderm (muscles, etc.) is the next to undergo this change and the endoderm (gut, etc.) the last. It seems very possible that the same sequence of changes would account for the separation of cells of different species according to the animal from which they were derived. If the changes occurred much later in the cells of one species than in the other, they would become separated. Such results are seen in the experiments on sponges. But if the changes occurred simultaneously the cells of the two types would form composite tissues as Moscona[5] found.

One immediately becomes curious as to what this change is; it appears to be connected with adhesion and movement, for the following reasons. Before reaggregation starts, the cells are non-motile and non-adhesive; they then become highly motile and rather adhesive and finally become immobile and very adhesive. Do these changes occur at different times in each cell type?

The first change appears to occur simultaneously in all cell types, but the second appears to happen at different times in each tissue. The reasons for thinking this are that Galtsoff[3] showed that the cell type that was outermost in sponge reaggregates was the first type to become sorted out and to cease movement. Likewise, in amphibian reaggregates the ectoderm reaches the outside and ceases movement before the muscle and gut cells have sorted out, and while they are still actively intermingling.

It appears that the sorting-out process starts with the immobilisation of ectoderm cells on their reaching the surface of the reaggregate. At this stage, other types of cell reaching the surface continue moving and so crawl back inside the reaggregate. Even if the cells move in random paths, as is most probable, this process will trap all the ectoderm cells at the outside. When the outer layer is full of trapped cells, the process shifts inwards and cells are caught against the outer layer; trapping thus moves inwards layer by layer. Early in the process, the ectoderm cells are the only trappable ones, but when they all have become caught, the mesoderm cells become trappable and are caught against the inner surface of the ectoderm. The endoderm cells are the last to change their properties and so form the core of a series of concentric tissues.

How do cells get trapped at the outside and later against already trapped cells? Early in reaggregation, all the cells move and are jostled and rubbed against on all sides, except when they are at the surface. Cells at the surface are only rubbed against—that is sheared—on their inner surfaces. When the outer cells are immobilised, cells trapped inwards of them are in turn caught against a surface which does not shear them. Is the important change in cells one by which they become immobilised by a reduction in the shear against them?

MECHANICAL EFFECTS ON THE CELL SURFACE

It has not yet been possible to answer the last question, but with the apparatus shown in Fig. 6 we find that shearing forces do affect the cell surface.[1] The technique used is as follows:

The small platinum ring is placed on the surface of a suitably large cell and then twisted by using a magnetic field to turn the magnet above the ring. When the field is removed, the magnet and ring swing back and oscillate, the oscillations dying away at a rate that depends on the viscosity of the surface.

Such measurements show that the

viscosity (which is determined by the surface structure) alters with the rate of shear, leading us to conclude that cell surfaces are affected by shear forces.

CELL ADHESION

Although doubt has been cast on several suggestions as to the mechanism of cell adhesion, additional positive evidence about such adhesion will now be described. The Japanese scientist Dan did a most complete series of experiments that were published in 1947. Placing sea-urchin eggs on glass, he found that the rate at which they were pushed off by a gentle flow of water was directly related to the potential of the electrical charge of the cell surfaces. The greater the surface potential the less adhesive were the cells, assuming, as was reasonable, that the rate of "pushing off" was a measure of adhesion.

This result may be explained simply in physical terms. If two surfaces bear charges of like sign they tend to repel each other. The negative charges on cells are produced by the ionisation of chemical groups in the surface. But what forces act to attract two surfaces? In many non-living colloidal systems van der Waals forces are thought to play this part. Derjaguin[2] describes these forces, which are electromagnetic in nature. In such systems they act in opposition to the repulsive forces due to the surface charges. The forces of each type between two surfaces tend to cancel out when the surfaces are a certain distance apart. When they cancel out, there is neither attraction nor repulsion between the surfaces. If the forces of attraction are larger at a slightly greater separation of the surfaces, any attempt to draw the surfaces apart is opposed and they are adhesive. In many non-living systems, the forces cancel out at a separation of about 100 Å (10^{-5} mm.).

This 100 Å separation of surfaces is also found to be the distance apart of cell surfaces in many coherent tissues when observed with an electron microscope. Hence it is possible that this system of forces acts in cell adhesion. (It can be argued, however, that there are great changes in the separation of the cells when they are prepared for electron microscopy.)

Since van der Waals forces would be expected to be of very similar value between all types of cell, the adhesive differences amongst cells may be due to differences in the repulsive forces between them. This would be caused by differing cell types having different potentials of surface charge, and such differences have been found between many cell types. For example, red blood cells which are normally non-adhesive have a far higher surface potential than liver cells which are very adhesive.

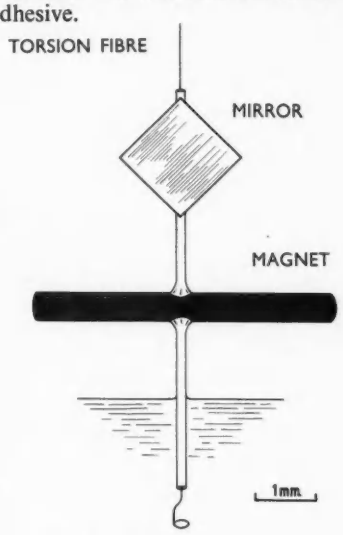


FIG. 6. Apparatus for measuring the surface viscosity of cells.

Calcium and magnesium lower the surface potential of cells, which explains how they make cell adhesion possible in reaggregation. Presumably the surface potential of the cells falls throughout the process of reaggregation, making the cells more and more adhesive. At first this steady change would make them adhesive enough to move easily, but later the cells would become too adhesive to move. The shearing action may play a role by affecting the charges on the cell surface and thus their potential. But we do not yet know why these changes in adhesiveness occur at different times in each cell type.

FUTURE DEVELOPMENTS

What has so far prevented the successful reaggregation of tissues from adult vertebrates? If such reaggregation were possible, the reaggregates might be used to repair serious wounds such as amputated limbs. For this purpose the cells of the damaged tissue might be salvaged, or cells might be taken from an intact limb and grown to increase their number sufficiently.

It is well known that during the healing of wounds some control is exerted over cell movements and adhesions so that skin, muscle, etc., end up roughly in the same place. In this respect, reaggregation and would-healing are very alike. As human wounds heal, the mobility of the skin cells dies away before they can cover all but small wounds. As a result, the gap in large wounds is covered by scar tissue. Is this too early loss of cell mobility akin to the temporal changes found in reaggregation? Possibly it is an explanation of the failure of reaggregation in adult vertebrate tissue, the cells losing their power of movement before any extensive sorting-out occurs.

A further complication may lie in the fact that many adult tissues contain a great deal of material in between the cells; for example, in bone or cartilage. Cells may be sparsely scattered through such material so that one cell is rarely closer than 2000 Å to another. In such tissues, the mechanisms of cell adhesion discussed above would not operate, and the cells are probably trapped in position in this material by reason of its very high viscosity. In order to get reaggregation in such tissues it would be necessary to get rid of the extracellular material and allow the cells to replace it in the reaggregate later.

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FIG. 1. The spiral galaxy NGC5194 (Messier 51) in *Canes Venatici*, with the companion or satellite galaxy NGC5195.
(*Mt. Palomar Observatory*)

THE CHARACTER OF THE UNIVERSE
–EVOLUTIONARY, STEADY-STATE, OR INDETERMINATE?–

W. DAVIDSON

On the basis of his latest measurements, Martin Ryle claims an "evolutionary" universe but Fred Hoyle argues that a "steady-state" universe could appear "evolutionary" with an inadequate statistical sample. W. H. McCrea predicts the answer will never be found because of a basic uncertainty in measurements.

The problem of the nature of the universe on the largest possible scale has intrigued inquiring minds since the dawn of civilisation. Today, the progress of science and technology encourages the belief that we may shortly find an answer to the age-old enigma. Through the advance of technology, the present century—and particularly the last decade—has brought us to the point where exciting scientific theories of the universe may almost immediately be tested by the intricate and painstaking techniques of modern observational astronomy.

It appears from recent developments that within the next decade we may determine whether the universe as a whole, despite its uniqueness, is susceptible to a scientific theory or is to remain as great a mystery as ever. The distinguished radio astronomer Martin Ryle recently claimed that he has now demonstrated that the universe is evolutionary in character, in accordance with one of the two rival theories held at present. This claim, it should be said at once, is strongly resisted as premature by the opposing "steady-state" school. On the other hand there is the recently expressed view by the eminent cosmologist William H. McCrea that there is an essential uncertainty, increasing with distance, in any observations of the universe, and that no exact or determinate theory will ever overcome it.

In this article the events leading to the present situation in cosmology will be reviewed. The two strikingly different rival theories that have commanded attention in recent years will be described and the ways in which they may be distinguished will be outlined. Finally, some general considerations bearing on prospects for the future will be discussed.

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THE EXPANDING UNIVERSE

It is generally agreed by astronomers that, to the utmost limits of their telescopes, the universe is populated by galaxies of stars similar to our own Milky Way, and that, apart from a tendency to group into clusters, they are distributed more or less evenly in all directions about us. The most significant observational feature of these galaxies is that the characteristic lines of their spectra, obtained when their light is passed through a prism, show a displacement towards the red end (that is, to longer wavelengths) when compared with the spectrum of light from stars in the Milky Way.

More than thirty years ago, the American astronomer E. P. Hubble made the celebrated discovery that this "red shift" increases systematically in direct proportion to the measured distance of the galaxy. This distance is determined from the apparent brightness of the galaxy when compared with that of a typical galaxy near us, such as the one in Andromeda, whose distance is known by similar considerations applied to stars of recognisable type within it. Recalling the familiar Doppler effect on the frequency of a moving source of sound, or of monochromatic light, astronomers concluded that the galaxies were receding from us at a speed proportional to distance, and this interpretation is now generally accepted.

Because of the approximately uniform distribution of observed galaxies, it was further inferred that this phenomenon would be seen from *any* galaxy, and we thus have the concept of the "expanding universe", probably the most profound challenge to theoretical interpretation in the history of science.

At this time scientists were encouraged by the brilliant analysis of space and time that had already been made by Einstein in his theory of relativity; Einstein had even put forward a static model of the universe before the Hubble expansion was discovered. This had given the clue to other theoreticians, notably the Russian mathematician A. Friedmann and the Belgian Abbé Georges Lemaitre, as to how the problem of a non static universe should be tackled. If the situation indicated by the astronomical observations were correct, then it followed from the work of these investigators that there must be an approximately uniform cosmic time in the universe common to all observers at rest in their galaxies, and that three-dimensional space must also be of approximately uniform character everywhere, but not necessarily flat and infinite as is the space of Euclid and Newton. Universal space could be *curved*, as already had been suggested by Bolyai, Lobachevsky, and Riemann. If the curvature were positive, then space would be finite although unbounded, in the sense that the Earth's surface has a limited area although it has no boundary; if the curvature were zero, space would be flat and infinite in just the way that Euclid and Newton had imagined it; and if the curvature were negative, then space would be infinite but would contain more volume within a given distance from the observer than in Euclidean space. A space of positive curvature would contain less volume within a given distance than Euclidean space (Fig. 2).

The theoreticians found that at a

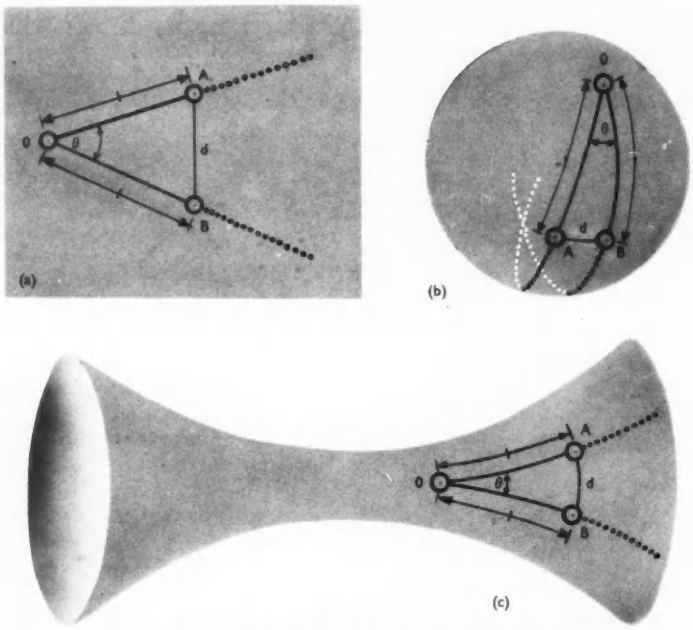


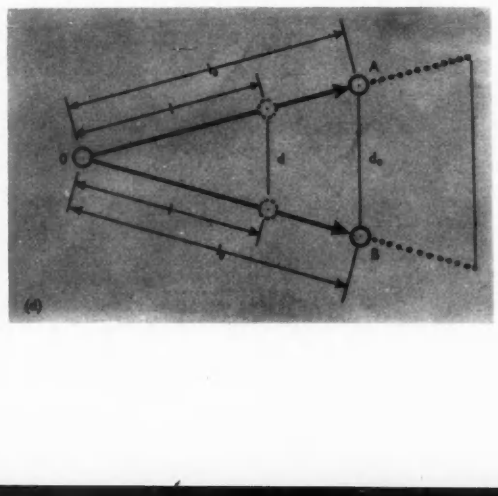
FIG. 2. Curvature of space: spaces of zero, positive, and negative curvature as illustrated by analogy with two-dimensional surfaces of ordinary experience—the plane, sphere and hyperboloid respectively. The three objects in the different spaces are O (the observer), and two adjacent galaxies A and B at the same very great distance from O.

(*a*) Euclidean space. If the two objects A and B are a (small) distance d apart and at equal (large) distance l from O, with OA and OB inclined at an infinitesimal angle θ, then in Euclidean space $d=l\theta$. The shortest distances OA, OB are straight lines and a circle of radius l centre O has a circumference of length $2\pi l$. The lines OA and OB, when extended, never meet again, that is, flat Euclidean space is *open*.

(*b*) Space of positive curvature. In the analogous situation of the sphere, the shortest (or geodesic) lines are great circles on the sphere, and in this case $d<l\theta$. A circle of radius l on the sphere has circumference $<2\pi l$. OA and OB, when extended, would meet at the antipodal point of O and finally meet again at O. Similar statements hold about a space of positive curvature, which is therefore *closed*. In a space of fixed positive curvature, it is possible for a ray of light to go round the universe and return to its point of emission.

(*c*) Space of negative curvature. On the analogous two-dimensional hyperbolic surface the adjacent geodesic lines OA and OB will not meet again. Here $d>l\theta$ and the circumference of the circle radius l is $>2\pi l$. Similarly, a space of negative curvature is *open*—a ray of light does not cross its path again.

(*d*) The expansion of space. Taking the Euclidean case as an example, the equal distances OA=OB=l of the two galaxies at the epoch of emission of their light are increased to l_0 by the time (the present) when the light is observed by O. Nevertheless, O *observes* the two galaxies as at distance d apart, and not at their "present" distance d_0 apart which is increased relative to d in the same proportion as l_0 to l.



given epoch such a universe would either be in general expansion or contraction, and the red shift or violet shift, respectively, would as a first approximation be proportional to distance, in agreement with observation. If space were curved and the universe expanding, the curvature would decrease in absolute value as the epoch advanced; if space were curved and the universe contracting, the curvature would increase.

Accepting expansion at the present time, cosmologists are now divided into two schools of thought supporting the two rival theories referred to earlier.

THE EVOLUTIONARY THEORY

The supporters of the evolutionary theory, which came first, believe that the matter-energy in the universe was created once and for all at a finite time in the past, in an explosive state of very high density and temperature. They believe, further, that the universe has been expanding ever since and will continue so into the future, where the process must either reverse and be followed by contraction or continue indefinitely to a state of infinite dispersion.

As implied above the evolutionary school are unable to predict a unique evolutionary model. But those, notably George Gamow, who rely on the original and perhaps most acceptable form of Einstein's equations of general relativity, omitting the so-called cosmological constant, are able to deduce that the recession of the galaxies must be slowing down (Fig. 3), the deceleration of a galaxy at a given epoch being proportional to its distance. Further, they can show that once the present scale of deceleration has been determined observationally, they can (given the present rate of expansion), determine the curvature of space, the present average density of matter, and whether the universe will ultimately begin to contract or expand to infinite dispersion. Extrapolating the present rate of expansion backwards, they are able to deduce that the start of the present expansion occurred less than twenty thousand million years ago (actually less than the reciprocal of Hubble's rate of expansion "constant", which on present estimates means less than 10 to 15 thousand million years ago).

Strictly speaking, of course, if the universe ultimately contracts we are free to suppose that the cycles of expansion and contraction have been going on indefinitely; that is, in a "pulsating" universe, the creation event would be repeated at regular intervals.

THE STEADY-STATE THEORY

The steady-state school, on the other hand believes that new matter is being created all the time at an extremely low, undetectable rate in the vast spaces between the receding galaxies, that new galaxies are continually being formed from the created matter, and that the universe in this way maintains, despite the expansion, a steady state of constant average density. Thus the steady-state universe is of infinite age and has the same general appearance at any epoch, although the individual galaxies may be of any age. The theory shows that the recession of individual galaxies steadily accelerates at a rate proportional to distance, the acceleration scale being constant and calculable exactly from the Hubble rate of expansion. Thus, galaxies at a given distance have always the same velocity and acceleration in a steady-state universe. The curvature of space is zero, so that space is infinite.

These properties of a steady-state universe were first deduced by Hermann Bondi and Thomas Gold. Fred Hoyle and W. H. McCrea were able to go further by applying general relativity to such a universe. In this way they were able to predict the constant average density of matter in terms of the Hubble rate of expansion, and also the rate of creation necessary to maintain the steady state.

OBSERVATIONAL TESTS

The present observational programmes of radio and optical astronomers in many parts of the world include extensive projects of cosmological significance. The issue between these two theories will almost certainly be decided, if it is to be decided at all, on a statistical basis—that is, not by a single dramatic test but by the gradual accumulating evidence of many tests of different character. Naturally, however, some tests may be expected to carry more weight than others.

While the present rate of expansion

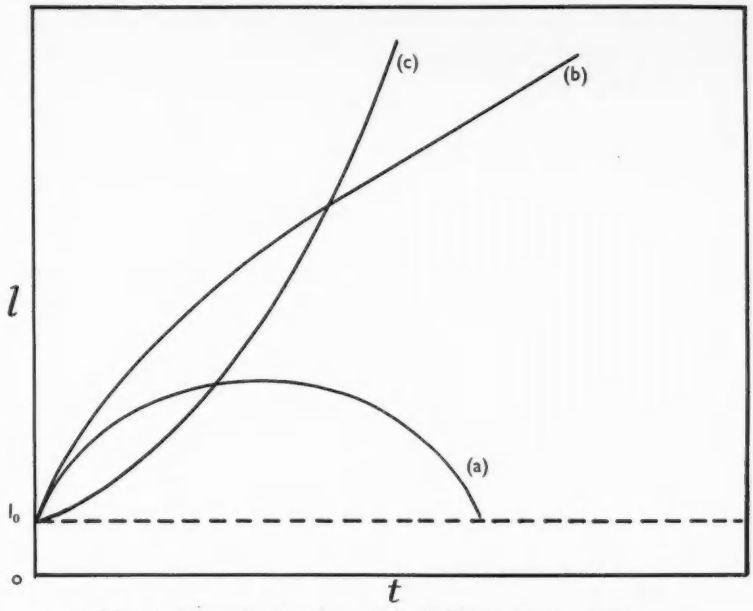


FIG. 3 (*above*). Curves showing the variation in distance between two galaxies with cosmic time, from the time when they were a small distance l_0 apart (exaggerated in diagram), for three cases:
(*a*) An evolutionary universe in which the expansion decelerates at a relatively high rate so that contraction ultimately sets in. The curvature of space is positive so that the volume of space is infinite.
(*b*) An evolutionary universe of more moderate deceleration in which the expansion continues indefinitely. The curvature of space is negative and its volume infinite.
(*c*) A steady-state universe in which the recession of individual galaxies must accelerate. The curvature of space is zero so that space is Euclidean and infinite.

Note: It is assumed here that the two galaxies do not belong to the same cluster, since there is strong evidence that galaxies in clusters do not share in the expansion of the universe because of the gravitational drag of the cluster. The clusters as a whole recede from one another according to the Hubble Law.

FIG. 4. Cluster of galaxies in *Corona Borealis* at a distance of 700 million light years and receding from us at 21,500 km./sec. The bright spherical foreground objects are stars of the Milky Way.
(*Mt. Palomar Observatory*)

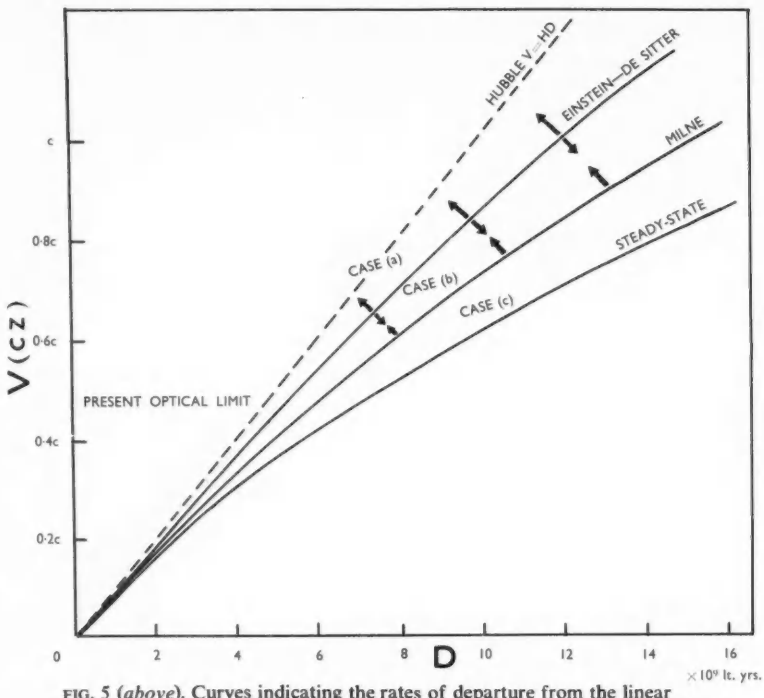
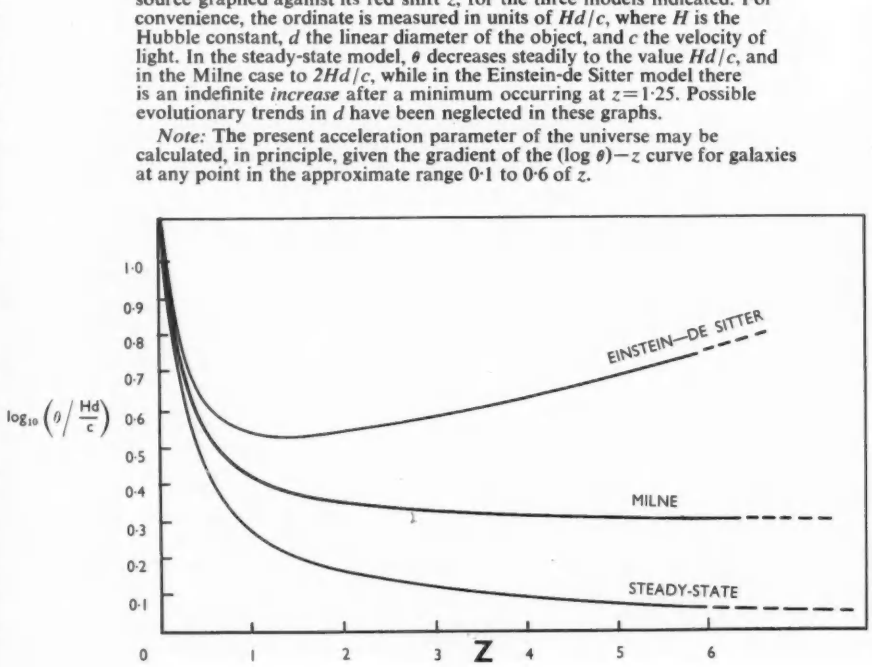


FIG. 5 (*above*). Curves indicating the rates of departure from the linear velocity-distance relation $V=HD$ for the three cases of Fig. 3. The velocity V is defined as cz, where z is the red-shift and c is the velocity of light. D is the "luminosity distance", which is basically a theoretical quantity depending on the cosmological model but is deducible from the apparent brightness of the source provided the evolution of its intrinsic brightness is known. It is the latter that is uncertain at present. The bounding curves of the regions corresponding to case (*a*) and case (*b*) are the V-D curves for the Einstein-de Sitter universe and the Milne universe.

FIG. 6. The logarithm of the angular diameter θ of a galaxy or radio source graphed against its red shift z, for the three models indicated. For convenience, the ordinate is measured in units of Hd/c, where H is the Hubble constant, d the linear diameter of the object, and c the velocity of light. In the steady-state model, θ decreases steadily to the value Hd/c, and in the Milne case to $2Hd/c$, while in the Einstein-de Sitter model there is an indefinite *increase* after a minimum occurring at $z=1{\cdot}25$. Possible evolutionary trends in d have been neglected in these graphs.

Note: The present acceleration parameter of the universe may be calculated, in principle, given the gradient of the (log θ)$-z$ curve for galaxies at any point in the approximate range 0·1 to 0·6 of z.



given by the Hubble parameter does not, at its present accepted value, distinguish the two theories in any way, one method of approach is to look to the acceleration of the galaxies which does. At least two ways are open to obtain this important quantity.

Velocity-distance relation from red shift and apparent luminosity. The first method is to graph the red shift against the apparent luminosity (brightness) of a galaxy as the luminosity decreases (so that the red shift increases). This has been done systematically in America, using the huge telescopes on Mt. Wilson and Mt. Palomar for a vast number of galaxies out to a distance corresponding to a recessional velocity of two-fifths of the velocity of light. Although this test has been interpreted as indicating a decelerating expansion, and therefore an evolutionary universe, it cannot yet be relied upon, unfortunately, because of the present uncertainty regarding the evolution of the intrinsic brightness of a galaxy (Fig. 5). Since the remotest galaxies seen now emitted their registered light over five thousand million years ago, this is clearly a pertinent problem; it will be solved only when the evolution of stars, at present receiving intense study, is thoroughly understood.

In an evolutionary universe, galaxies would be expected to evolve collectively; in a steady-state universe, on the other hand, they must evolve individually, so that in a sufficiently large region we should expect to find a wide variation of age—the very old with the very young. This fact in itself may yet provide a criterion to distinguish the two types of universe. As it is, neglect of collective or individual evolution in the test described above leads to too low a value for the "acceleration parameter", and the present evidence indicates that this error could be quite large.

Measurement of angular diameters or angular separations. A most promising alternative method is to measure the angular diameters of galaxies, and even of clusters of galaxies, as a function of either red shift or apparent luminosity. An equally valuable programme which should theoretically provide the acceleration parameter will be the measurement in a similar manner of the average angular separa-

tions of galaxies, and of clusters of galaxies. Since observations of the very distant regions of an evolutionary universe should reflect the congested state of the galaxies nearer the time of the creation event, whereas conditions in a steady-state universe at remote epochs should appear to be the same as obtain locally now, it is clear that we have here, in principle, a powerful criterion to distinguish the two universes. The encouraging feature is that, since the acceleration parameter for a steady-state universe is known in advance, the expected graphs of angular diameter or angular separation against red shift or apparent luminosity are quite definite for this model (*cf.* Fig. 6).

While only a little work has yet been done on these lines in the optical field, the systematic measurement of the angular diameters of radio sources is now being carried out by H. P. Palmer and others at Jodrell Bank, using interferometer methods. This programme should prove to be a very fertile one. A feature of immediate value arises as follows.

It has been shown theoretically, by Fred Hoyle and by W. Davidson, that if the huge radio source in Cygnus (identified as two colliding galaxies at a distance from us of about seven hundred million light years) is typical in size of the very distant radio sources that have been recorded, then the limiting angular diameter of such sources in a steady-state universe would be non-zero, between two and four seconds of arc depending on the shape of the source. Indeed, if the red shift is known, the expected angular diameter of any source is calculable and should decrease steadily to this lower limit as the red shift increases to infinity (Fig. 6). Consequently, any wide divergence from the calculated formula would rule out the steady-state model, and agreement with it, within observational error, would support it. Since similar formulae may be derived for certain evolutionary models, this test may therefore prove to be a very valuable one.

It has already been noted that three well-known evolutionary universes—namely the Einstein-de Sitter, Milne, and Dirac models—appear to be inconsistent with the preliminary Jodrell Bank data. The steady-state model, on the other hand, does not appear to be inconsistent with the data, but it is too early for any definite conclusions.

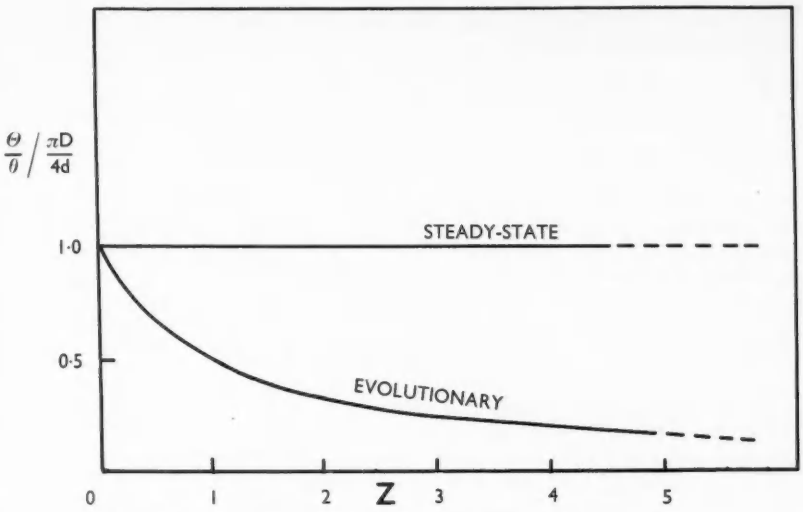


FIG. 7. Curves of the ratio $\Theta:\theta$ against z in the steady-state model and any evolutionary model, where Θ is the mean angular separation of the cosmic objects (galaxies, radio sources, clusters) and θ is the angular diameter of these objects. The ordinate is measured in units of $\pi D/4d$, where D is the average linear separation of the objects at the present epoch and d is their average linear diameter, any evolution in d in the case of the evolutionary models being neglected.

The present Jodrell Bank programme should also provide a more accurate knowledge of the range of intrinsic luminosity of radio sources, so vital for the interpretation of many observational tests. Given the angular diameter, red shift, and apparent intensity of a source, its surface brightness may be calculated. It has already become clear that there are many sources in the sky with an intrinsic power approaching that of Cygnus A. It has been pointed out by Davidson that the particular source 3C 295, whose recently detected recessional velocity is nearly half the speed of light, must be at least twice, and is probably five times, as powerful as Cygnus A. This indicates that the dispersion of luminosity may be wider than has been anticipated. On the other hand, if a definite trend to greater average intrinsic brightness were detected with increasing distance, assuming the absence of any selection effect, this would indicate an evolutionary universe.

A most promising criterion involving the angular measurements of radio sources is the significant difference expected between the evolutionary and steady-state models for the ratio of the mean angular separation of the sources in a given region of space to their mean angular diameter in that region (Fig. 7). As has been shown by P. S. Florides and W. H. McCrea, this ratio should remain constant, independent of the distance, in the steady-state model. In all evolutionary models, the ratio would be expected to tend steadily to zero as the distance increased, for the following reason: while the average distance between sources would decrease as we look backwards in time towards the creation event, the intrinsic size of a source would not be expected to vary nearly so rapidly.

Number-count relations. We now come to an observational test that has recently caused great excitement and controversy. The object here is to count total numbers of galaxies or of radio sources as a function of apparent luminosity or apparent intensity. Given the average intrinsic power and average spectrum of the sources, a definite curve can be predicted for the steady-state model. (Curves for evolutionary models depend on possible evolutionary trends in the total power and in the spectrum.) Very great care, however, has to be taken that neither selection effects nor systematic instrumental errors enter into the observations. Thus, in the case of radio sources, this method of distinguishing the models is naturally reliable

only if the total number of sources in a given, and exactly measured, range of intensity is counted. In earlier surveys there seemed good reason to believe that confusion of sources due to overlapping was a real hazard at low intensities.

In the latest results obtained at 178 Mc/s by the new, very sensitive interferometer at Cambridge since 1958, Martin Ryle and his colleagues are confident that all sources of possible error have been allowed for and do not affect a clear-cut conclusion that the steady-state model is incompatible with the actual universe.

The problems to be tackled and the procedure followed by Ryle and his associates were as follows.

Firstly, they had to determine the distribution of intrinsic radio brightness, the "luminosity function" of the sources. Without making assumptions about the nature of the sources, they were first able to deduce that only a small fraction of those observed in a given range of flux density could be within the Milky Way. In fact, they could show that most of the sources must have an intrinsic radio luminosity at least a thousand times that of the galaxy (the galaxy having an emission of about 10^{21} watts/unit frequency/steradian at 178 Mc/s) and, therefore, that those of low apparent intensity could be detected to distances of relevance to the cosmological problem. Further, by a more extensive optical analysis of identified sources, and by measurements of radio surface brightness (in the manner referred to earlier, assuming an intrinsic average size of galactic dimensions) they were able to conclude that the average radio luminosity is at least 10^4 to 10^5 that of the galaxy and might be as much as 10^6 times as high if the certain identifications were regarded as a typical sample.

The second problem was to examine possible instrumental effects, and errors in interpretation due to confusion—for example, the misinterpretation of a distant cluster of sources as a single nearer bright source.

Finally, they had to derive the actual number of sources falling in different ranges of flux density so that the results could be compared with the predictions of the steady-state model after the necessary corrections had been made.

With the new instrument, sources can be detected individually down to a flux density of 2×10^{-26} watts/cps/m^2. At this level, there is still only one source per thirty beam areas and the signal-to-noise ratio is 25 to 1. With such a large signal-to-noise ratio, it was possible to get statistical information about the distribution of the weaker sources (using a method first developed by P. Scheuer in 1957) down to a level at which there are about 250,000 sources in the whole sky.

Ryle concludes that even if the lower limit for the radio luminosity function (derived without assumptions regarding the nature of the sources) is adopted, the observations imply a very considerable excess of sources at great distance over those nearer at hand, contrary to the even distribution appropriate to the steady-state model. In fact, as the graphs show (Fig. 8), the observed number of sources down to the level at which individual sources can be distinguished is $3\pm0{\cdot}5$ times that predicted by the steady-state model. If a luminosity function similar to that of the identified sources is assumed, the discrepancy factor is 11 ± 2.

Resisting Ryle's conclusion against the steady-state model, Fred Hoyle has recently put forward a theory of how a steady-state universe could appear to be evolutionary under Ryle's observations if an inadequate statistical sample were taken. In this new interpretation of the steady-state model, Hoyle opposes the widely held view that the observed clusters of galaxies are the largest aggregates in the universe. He now believes that most of the clusters are in fact sub-units in larger associations of about 100,000 galaxies of comparable age. These larger units—about 10^8 light years in diameter when first formed—expand with the universe, and are necessary in Hoyle's view in order that galaxies should be reproduced at all in the steady-state cosmology.

Hoyle then conjectures that any galaxy may become a radio source as a stage in its evolution. In order to fit Ryle's data Hoyle has to suppose that the probability of becoming a radio source has a relatively very high maximum at an age between 10^{10} and $2{\cdot}5\times10^{10}$ years. Consequently, only associations in this range of age at the epoch of emission of observed radiation will exhibit a high proportion of radio sources. Our neighbourhood is not in such an association, Hoyle claims, and hence we find a relative dearth of radio sources nearer at hand. Furthermore, he asserts, with a suitable choice of the disposable parameters this steady-state model can be made to agree statistically with Ryle's results for the same range of observation.

Ryle has offered immediate objections to this theory. He questions whether a local deficit of sources due to associations on the scale postulated by Hoyle could be found without, at the same time, evidence of anisotropy in the distribution of the sources, which he himself has been unable to detect out to the full extent of his survey. Again, he doubts whether enough of the galaxies in such an association could coincide in reaching the radio stage during the 10^7 years or so which, on energy considerations, appears to be the maximum possible lifetime of a radio source. Furthermore, he believes that Hoyle's curve fitting depends on too low a choice for the intrinsic luminosity of the sources for compatibility with the observational data.

Certainly the question of the luminosity function of the sources is highly relevant to the whole interpretation of Ryle's results, and this appears to be, if anything, the most vulnerable point in Ryle's formidable case against the steady-state model, and also of Hoyle's defence of it. In addition, if Hoyle's large-scale associations cannot be observed as such, his theory will lack the observational support essential to a useful scientific theory.

If future observations confirm that the luminosity function of the sources is more extensive at the upper end of the distribution than it is thought to be at present, it appears just conceivable that Ryle's results could be explained in a steady-state universe without associations of the sources—as a selection effect equivalent to confusion of distant sources. Only the most careful analysis of Ryle's data and arguments and those of the steady-state school can decide this whole issue.

GENERAL CONSIDERATIONS AND FUTURE PROSPECTS

It was stated earlier that the Hubble constant does not distinguish the two theories at present. However, if, as

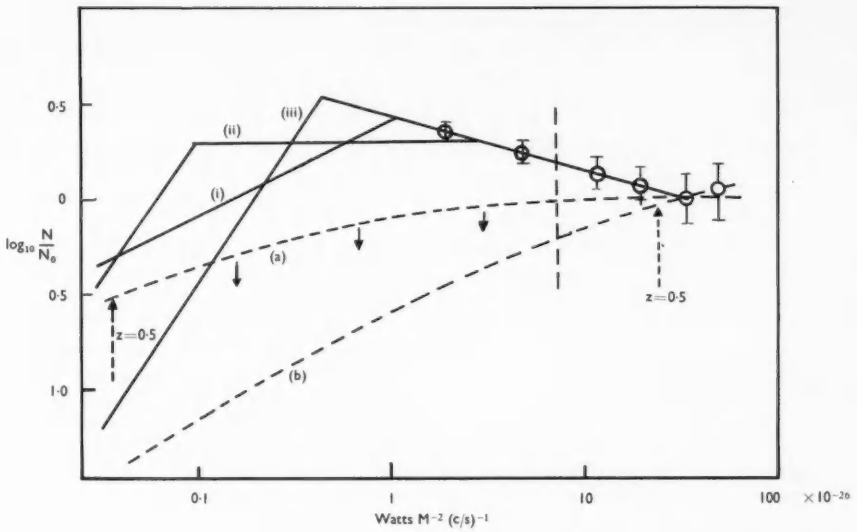


FIG. 8. Ryle's curve (solid line) with limits of estimated error indicated of the number counts of radio sources as a function of apparent intensity at 178 Mc/s. The ordinate measures $\log_{10}(N/N_0)$, where N is the total number of sources down to the apparent intensity indicated by the abscissa and N_0 is the comparison number calculated for the same type of course in a Euclidean non-expanding universe. The curve is extended beyond the intensity 2×10^{-26} W/m^2 cps by statistical analysis of the records, yielding extensions (i), (ii), (iii) according to the assumptions made. The dashed curves are those calculated by Ryle for the steady-state model; the upper one (*a*) is derived assuming the lower limit for the possible intrinsic power of the sources, and the lower one (*b*) is derived assuming the intrinsic power indicated by the identified sources. The vertical dashed line indicates the limit of the earlier surveys.

(Diagram by courtesy of Prof. Ryle and the Royal Astronomical Society)

Hoyle has recently suggested, the age of the galaxy may be as much as $2{\cdot}5\times10^{10}$ years (the recently determined best estimate by Hoyle and Fowler being $1{\cdot}5\times10^{10}$ years), this would rule out the decelerating evolutionary universes of the Gamow type unless the reciprocal of the Hubble constant were also raised to this value. Both the Hubble constant and the age of the galaxy may be expected to be much more accurately determined within the next few years.

Since the evolutionary models of the universe are generally studied by means of the field equations of general relativity, a recent development of relativistic cosmology by W. B. Bonnor is worthy of note. Bonnor has shown that in a relativistic cosmological model in which the average pressure is not regarded as negligible, the evolution of the model from a given state at a given epoch is not uniquely determined in general relativity theory merely by imposing continuity of all the field variables and their derivatives.

This is an interesting result since it suggests (although Bonnor does not draw this conclusion) that general relativity is too general, and that the uniqueness of the universe demands a modification of at least the interpretation of general relativity, and also possibly of its formal content, so that it may only be applicable to the universe as it actually is. Indeed, general relativity has been developed from local physics (special relativity) at the contemporary epoch, and it is, of course, an epistemological argument for the steady-state theory that this cosmology, if established, would remove the doubt about applying the physics of local space-time to the universe.

The whole interpretation of cosmology has recently been questioned by W. H. McCrea. McCrea asserts that there is an uncertainty of knowledge of the factors affecting the physical conditions in those remote parts of the universe which we now see at an early stage in their history, due to the fact that light is propagated with a finite velocity. We cannot observe, McCrea remarks, any part Q of the universe in the state in which it was when it propagated its influence on any other part P of the universe, except when P is our own neighbourhood. He suggests, therefore, that there is a basic uncertainty in our predictions, which will increase with the red shift, and this uncertainty should be incorporated in any satisfactory cosmological theory.

A rejoinder to this has been made by Davidson. If we adopt the cosmological principle (assumption of cosmic uniformity) which is theoretically simplest and whose validity statistically is strongly suggested by the observational evidence, then there need be no uncertainty in predictions if we formulate a definite theory based on this principle. According to the cosmological principle, any part of the universe at a given epoch must be physically identical with our own neighbourhood at that epoch. Such theories—the steady-state theory in the Bondi-Gold form, for example—can then be tested observationally and can be rejected only if the universe is found to be inconsistent with its definite predictions, within reasonable statistical error, in accordance with accepted scientific principles.

This latter viewpoint has recently been supported by B. Balazs and Gy. Paal. They suggest that McCrea is confusing the logical issue in that he is inserting the uncertainty of his own preferred cosmology into the present well-defined theories of cosmology.

CONCLUSIONS

The present state of cosmology is a very fertile one with respect to relevant observational data. This circumstance fortifies the hope, and indeed justifies optimism, that within the next decade a theory that fits these data may be agreed upon. Should this fail, there is the reassurance, looking back, that scientists have always striven to acquire knowledge, despite "uncertainty principles". The field of cosmology will be no exception.

URANIUM, PLUTONIUM, AND NUCLEAR BREEDERS

LONG-TERM PROSPECTS FOR NUCLEAR POWER IN BRITAIN

J. L. GILLAMS

Once nuclear power "breaks even", demands for uranium should grow quite rapidly. As uranium reserves are depleted, it will be necessary to use reactors which make better use of their nuclear fuel. These "breeders" will produce additional fuel from the non-fissionable U-238 that constitutes more than 99% of the uranium found in the natural state.

We are at present in a period which, to the eyes of history, will probably appear as a short interval when nuclear power was technically feasible, but more costly than conventional power in most circumstances and places. The 1960s will be the testing time. At this moment we have two nuclear stations operating in Britain, Calder Hall and Chapelcross, while the first two Generating Board stations are nearing completion. By the end of the decade there should be fourteen nuclear stations operating altogether and their costs are expected to show a steady decline. Table I lists estimates of the capital cost of successive stations of the natural uranium magnox type. Although some of these estimates are under review and may ultimately turn out a little higher, the table clearly illustrates the downward trend:

Table I—ESTIMATED CAPITAL COST OF NUCLEAR STATIONS IN THE U.K.

Station	*1st Reactor On Power*	*Nominal Output MW(E)*	*£/kW*
Berkeley	1961	275	160
Bradwell*	1961	300	159
Hunterston	1963	300	?
Hinkley Point	1963	500	133
Trawsfynydd	1963	500	123
Dungeness	1964	550	110
Sizewell*	1965	580	100–105
Oldbury	1966	550	100?
Wylfa Head?	1967	800?	90–95

* See Fig. 1

Fuel costs will also fall as advantage is taken of lower market prices for uranium, and as manufacturing overheads are written off. These trends should lead by the end of the decade to generating costs (at 75% load factor) within the expected range of base-load costs at the most up-to-date coal-fired stations (built on or near a coalfield) to have been developed by that time. The break-even date may be later in other countries. The situation in Britain is rather favourable for nuclear power. A well-connected national grid leads to high load factors being available, while large power stations of 500–1000 megawatts (electrical) output can be accommodated, money is comparatively cheap, and conventional fuel prices fairly high. The break-even date for other applications of nuclear power will come later.

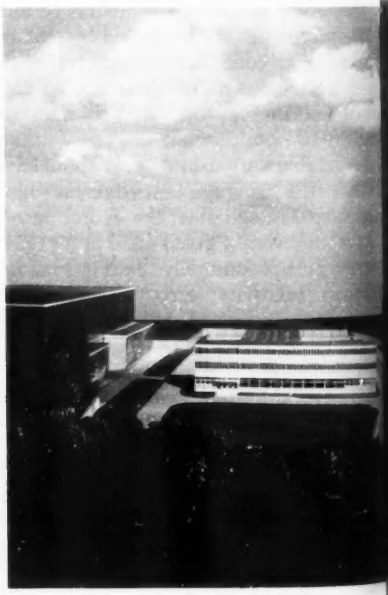
Present estimates of nuclear costs are based on assumptions which may prove conservative. If, as recent Calder Hall experience would suggest, load factors of 85 to 90% can be achieved, or if the nuclear stations last as long as conventional stations instead of the much shorter period of twenty years which is assumed in present cost calculations, the resulting advantage would tip the scales decisively in the favour of nuclear power. Fig. 2 illustrates the range of possibilities which are still open, in assessing the break-even of base-load nuclear and conventional power. It can be seen that there is a good prospect of reaching the break-even point in about ten years' time.

PROSPECTS FOR THE 1970s: PLUTONIUM-BURNING

Once the competitiveness of nuclear power has been established, the rate of nuclear installation should grow quite rapidly. It seems probable that virtually all new nuclear stations at that time will use enrichment in some form—that is, a higher concentration of fissile material than that found in natural uranium. It seems difficult to design for the austere neutron economy of natural uranium and, at the same time, achieve high thermal efficiency and high burn-up. Any discussion of the longer term prospects must therefore include problems of fissile material supply and lead on to the broader question of higher fuel utilisations.

Enrichment in any form is expensive. At present the only proven method is to use U-235 and it will probably be well into the 1960s before any other method is introduced on a large scale. Leaving aside the faint possibility of a technological breakthrough in uranium centrifuges, the U-235 can only come from gaseous diffusion plants which exist at present only in the U.S.A., the U.K., and the U.S.S.R.

There is, however, an alternative source of enrichment. This is the plu-



J. L. Gillams, M.A. holds a senior appointment in the London headquarters of the U.K. Atomic Energy Authority.

tonium by-product available to any nation with uranium-fuelled power reactors. Successive neutron capture results in the formation of the isotopes Pu-239, Pu-240, Pu-241, and so on, in turn. The odd-numbered isotopes of plutonium are fissile in slow-neutron or "thermal" reactors, and all of the isotopes of plutonium are fissile in fast reactors. The special problem in Britain is that plutonium from the national power programme will be accumulating on a very substantial scale; and it is thus desirable that we make the best use of this we can. Indeed, the nuclear generating costs in Fig. 2 would be nearly 10% higher if there was not sufficient faith in the future of plutonium as a reactor fuel to justify substantial repurchase credits for irradiated fuel.

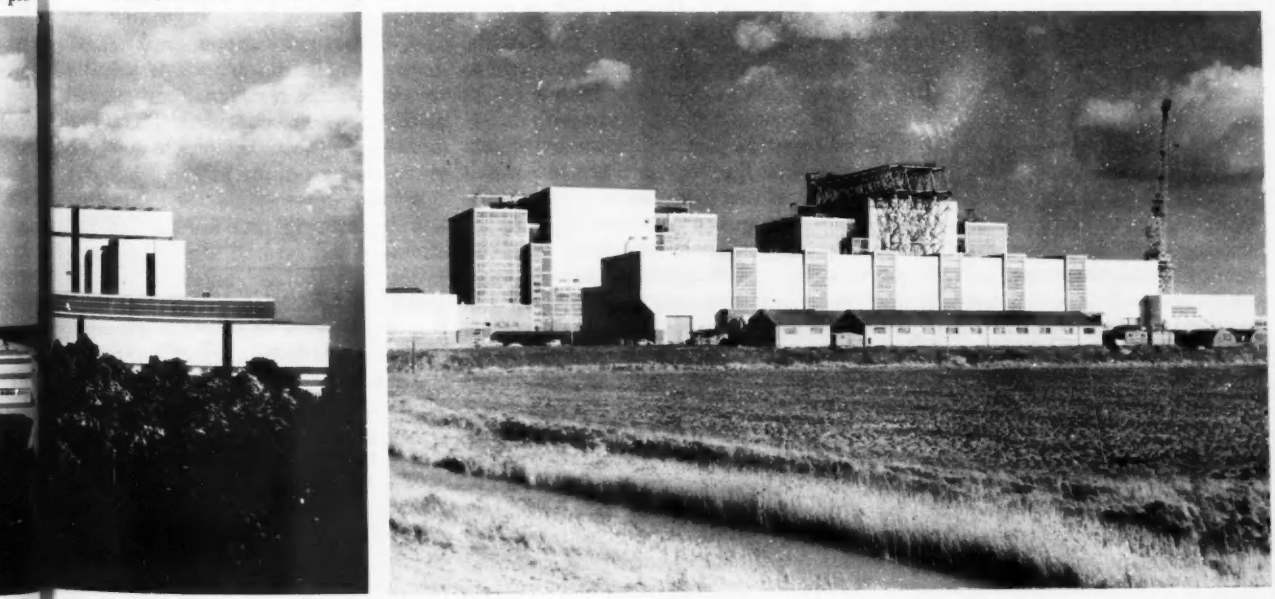
Fig. 3 illustrates the problem by showing the approximate cumulative build-up of plutonium output from the stations in the U.K. nuclear power programme. If the whole of this amount were purchased at £5000/kg., which is the basis of current U.K. repurchase terms for plutonium-bearing irradiated fuel, the stockholding could be in the region of £100 million in fifteen years' time.

Just how fast plutonium supplies will increase during the 1970s will depend on what share of the annual building programme of 3000–4000 MW(E) will be nuclear, and on the types of reactors, the load factors achieved, and the burn-ups attained. Thus the annual by-product of plutonium per 1000 electrical megawatt-years will range from as much as 600 kg. Pu (at an early magnox station at 3000 MWD/T) to 450 kg. Pu (at the sort of magnox station which might be built in the late 1960s if it were to burn to 4500 MWD/T) and to about 200 kg. (for an Advanced Gas-cooled Reactor station with stainless steel canned enriched UO_2 fuel and long irradiation). These differences are due to improvements in thermal efficiency, to differences of neutron economy and to the greater burning of the plutonium itself at longer irradiations.

The rate of plutonium accumulation might become an important limitation on the pattern of nuclear development in years to come. The U.K. Atomic Energy Authority is proceeding with some urgency on the development of the plutonium-burning fast reactor in the belief that this could be as cheap or cheaper in generating cost than any other reactor, and in the knowledge that a full demonstration of the merits of the fast reactor will be required before there can be a widespread changeover to that type of power station. There is reason to hope that fast reactors will be compact and cheap to build (quite apart from their breeding characteristics discussed below), have high thermal efficiencies, high burn-ups and low fuel costs. The inherent potential of the system therefore merits investigation.

Early fast reactors will, however, be heavy users of plutonium. High thermal ratings may only be achieved after several stations have been built, because of the formidable problems of rapid heat transfer in the restricted space of an unmoderated core. Burn-ups may also be low at first, and fuel manufacturing pipelines will have to be filled. As a result large fast reactor stations in the early years will each need something like 5 tons of plutonium. When this requirement is compared with the cumulative amounts shown in Fig. 3 it becomes clear that appreciable stockpiling will be required if fast reactor construction programmes are not to be held back for lack of supplies. It would

FIG. 1. Cheaper nuclear power is expected to result from increasing compactness of design. This can be seen from a comparison of the Bradwell station which will be commissioned next winter (*right*) with a scale model of the Sizewell station (*left*) which is scheduled to start generating power in 1965. Although Sizewell will have almost twice the generating capacity, it is smaller in size.
(left photo) English Electric, Babcock & Wilcox, Taylor Woodrow Atomic Power Group.
(right photo) Nuclear Power Group



be uneconomic to use U-235 in this context. An alternative use for plutonium may be to replace the U-235 enrichment in thermal reactors, possibly in the 800°C High Temperature Gas-Cooled (H.T.G.C.) reactors. It is too soon to say. The main point is that a large part of the nuclear power construction in Britain during the 1970s seems likely to depend on U-235-enriched thermal reactors (their generating costs aided by such plutonium credits as can be attributed to plutonium-burning at that time) and a small number of plutonium-burning stations whose capacity may be limited by the plutonium supplies available.

LATER PROSPECTS

As nuclear power programmes expand all over the world, the cheap reserves of nuclear fuel will gradually be exhausted, uranium prices will rise, and higher efficiencies of fuel utilisation will be needed. The time when this will happen is still far away, although it may have some influence on present reactor thinking. Annual production of uranium in the free world is of the order of 40,000 short tons U_3O_8/annum at the present time. If all this were to go to civil uses, it would support a nuclear installation equal to a good proportion of the entire electrical capacity of the United States—say 100,000 MW(E), increasing at 10,000 MW(E)/annum, the actual amount depending on the reactors involved. With nuclear power expected to break even with conventional power in many areas of the world in fifteen to twenty years' time, it will still be twenty-five years or more before nuclear installations are seen on this scale. Thus the time of rising prices (in the absence of overwhelming military demands for uranium) is still far away. Its advent will depend on the extent to which plutonium-burning increases the efficiency of utilisation of uranium, and also on the use of thorium, a nuclear fuel which is associated with a further fissile by-product, U-233.[1]

Nevertheless, the very long term prospects for nuclear power, and the type of reactor which should be developed to meet its needs, will inevitably depend in part on the future uranium market. A recent forecast[2] suggests that between 2 and 5 million tons of U_3O_8 reserves will be available in the non-Communist world at prices not exceeding \$10/lb. U_3O_8. Even the lower of these figures is impressively great, and may be compared with the output of 40,000 short tons/annum discussed above. It thus appears that there is every chance of prices remaining below \$10/lb. until some time in the next century. After that it will become important to have reactors which make better use of the reserves.

BURNERS AND BREEDERS

In a typical thermal reactor, something like three-quarters of a kilogram of plutonium is made for each kilogram of U-235 destroyed, so that there is a steady conversion from one fissile material to the other. For this reason these reactors are sometimes known as 'converters'. Reactors which burn with little or no conversion or without recovery of by-product fissile material are known as 'burners', and reactors which burn with a conversion greater than unity are known as 'breeders'.

There are some interesting problems on the optimum relation between converter and breeder reactors which will have to be worked out in years to come, including the problem of plutonium availability during the 1970s which has been mentioned already. The point of interest in this discussion is that the breeders make better use of the uranium. Fig. 4 shows the effect of rising uranium prices on the competitiveness of various types of nuclear power with conventional fuel. The thermal reactors would gradually become uncompetitive as uranium prices rise above present levels, fundamentally because their utilisation of uranium is poor. The greatest fuel utilisation which a converter of the type mentioned above could achieve would be about three times the original U-235 content of the fuel.[3] All but a fraction of 1% of the uranium is rejected from them, either as unrecovered irradiated fuel or as diffusion-plant waste during the process of enrichment. On the other hand, the uranium utilisation of the plutonium-burning fast reactor is good. This is because the system is a breeder, and achieves a net production of fissile material from the non-fissile U-238.

It follows from this that even if we can find out how to burn plutonium as fuel in thermal reactors, we shall still have learnt to burn perhaps only 1% of our nuclear reserves. The long-term necessity to do better than this is illustrated in Table II, which compares recent estimates of the energy content of free world coal reserves (at present and at twice present prices) with the energy content of reasonably assured uranium reserves (at present prices as

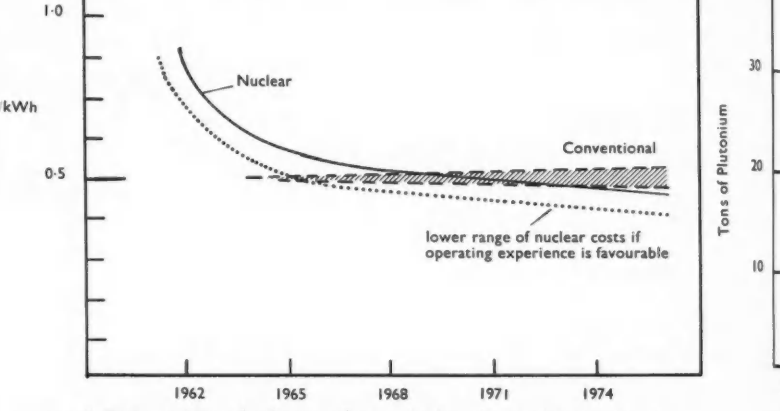


FIG. 2. Estimated base-load generating costs of nuclear and conventional power from stations brought on the line in the years indicated.

Table II—COMPARISON OF COAL AND URANIUM ENERGY RESERVES IN THE NON-COMMUNIST WORLD

B.T.U.s from Coal		*B.T.U.s from Uranium at present prices*	
At present prices	At double present prices	With 1% utilisation (converter)	With 5% utilisation (breeder)
$1{\cdot}5\times10^{18}$	22×10^{18}	$0{\cdot}6\times10^{18}$	30×10^{18}

used in either converter or breeder systems).

It is estimated that at least ten times more energy reserves would be available from uranium at higher prices, whereas further increases in coal prices would not release substantially greater reserves.[2] The ultimate extent of energy reserves in oil is not known, but they are unlikely to be greater than the energy reserves in coal. Thus it seems that nuclear fuels are by far the largest potential source of energy.

Only by using a breeder reactor will the ultimate ideal of very high utilisations of nuclear fuel be achieved. Massive programmes of breeder stations will need enormous stockpiles of plutonium for their fuelling, which will probably be drawn from earlier breeders as rising uranium prices inhibit the construction of thermal converters. With the long doubling times with which practical breeders are likely to increase their original fissile inventory, this implies that the first breeder reactors must be brought into operation several decades before any serious shortage of nuclear fuel occurs. This is a most important argument for devoting resources to breeder development today. Nevertheless the immediate incentive to develop breeder reactors is the hope that they will generate power at lower costs than thermal converters fed with cheap uranium. If that were not the case, the development of the breeder could be allowed to proceed at a slower rate more akin to the expected rise in future uranium costs.

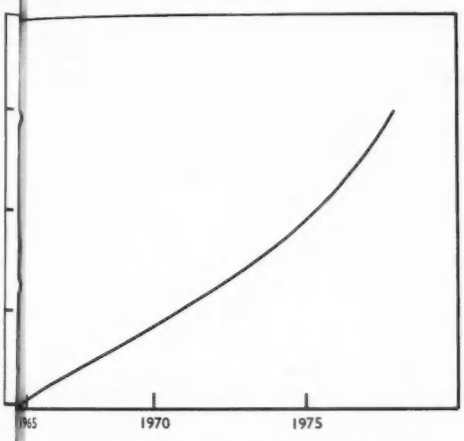


FIG. 3. Illustrative cumulative plutonium production from civil stations.

CONCLUSIONS

After about ten years of development, nuclear power stations will soon be coming into operation in increasing numbers, and their economic prospects should become more clearly understood. With the threat of a shortage of conventional fuels now deferred for several decades, nuclear power has to stand its ground in a competitive three-fuel economy. It seems that the large base-load power stations should break even at about the end of the decade. Applications to smaller power units should begin to compete successfully some years after that. The rate of nuclear installation seems likely to grow during the 1970s so that first the national base load and later some of the more intermittent demands are met with nuclear stations. As cheaper and more advanced nuclear stations are developed, this should lead to a small but definite reduction in the overall cost of power. If energy demands in the less developed countries follow the rapid rate of the Western industrial nations, an economic way of using nuclear fuels will one day be essential. And then, as cheaper uranium ore reserves are exhausted, it will become necessary to burn at greater efficiencies, and the breeder systems will come into their own, if indeed they have not already done so in straight competition with converters.

The ultimate benefit of nuclear power may therefore be the permitting of the widespread use of energy on a prolific scale throughout the whole world—at costs no greater than they are at the present time. Such a diffusion of the intensive industrialisation now characteristic of the Western democracies would be a revolution in itself, in some ways akin to the revolution which followed the introduction of steam. In Britain itself, the cleanliness of nuclear power generation will be increasingly attractive. Other benefits, possibly of less advantage to the human race, may be more spectacular, ultimate advantage of the compactness of atomic energy being taken by the nuclear-engined rocket. In the process of developing these new technologies, there can be no doubt that ancillary benefits will spread throughout the whole domestic and industrial scene.

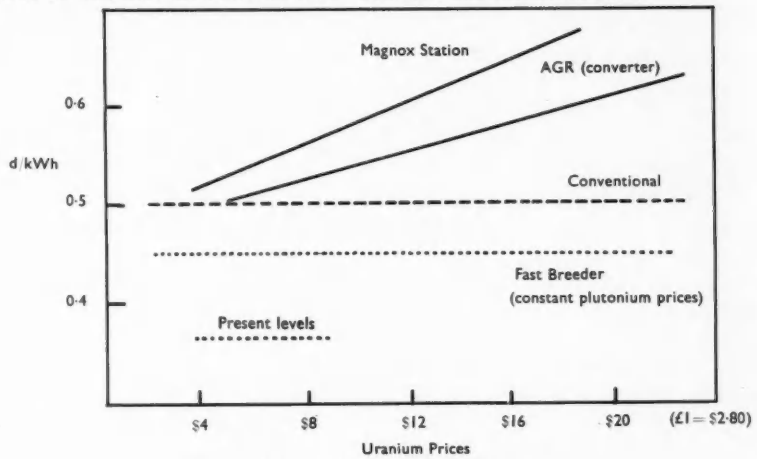


FIG. 4. The effect of rising uranium prices on nuclear generating cost.

NOTES

[1] Thorium occurs both in uranium deposits and on its own, and there is reason to hope that world reserves will be substantial, even if not as great as those of uranium. Except in those countries which have thorium deposits without uranium, there seems no particular urgency to develop the U-233 system. Nevertheless, this alternative fuel does hold out promise both in H.T.G.C. reactors charged initially with either U-235 or plutonium, and possibly as an alternative to diffusion-plant waste in the breeding zone of plutonium-charged fast reactors.

[2] U.S. Atomic Energy Commission Report TID-8207, May 1960.

[3] In fact a converter reactor with conversion factor C would ideally produce in successive fuel cycles a total quantity of fissile material equal to $C+C^2+C^3+\ldots$. $C/(1-C)$. Thus if $C=\frac{1}{4}$, 3 times the original U-235 loading would ideally be consumable.

AN ECONOMETRIC MODEL OF GROWTH
—THE BRITISH ECONOMY IN TEN YEARS TIME—

RICHARD STONE

Until the development of large electronic computers, detailed analyses of the economic system were too complex to be attempted. This article describes the beginnings of an econometric study that is being undertaken at Cambridge with the help of the computer EDSAC.

Economic growth is recognised nowadays as a desirable object of policy, and it is therefore important to discover what is involved in trying to increase it. With this in mind, a group of us at the Department of Applied Economics in Cambridge are engaged in building an econometric model of the British economy which concentrates on its productive aspects: the goods it must deliver and the resources it must absorb to make this possible.

Let us first be clear about what distinguishes this model from long-term economic forecasts as these are generally understood. Such forecasts tend to say: "If you behave so and so you will achieve such and such results." Behaving so and so usually means that affairs will be conducted much as they have been in the past and that nobody will have to take any very novel step. The present model says: "If you want to achieve such and such results you must behave so and so." In other words, it sets out to examine the implications of alternative rates of growth, some of which could never be achieved with a continuation of existing attitudes.

The reason for this inversion of emphasis is obvious enough. If everyone is satisfied with the present state of affairs there is little point in studying alternatives. If, on the other hand, one is not satisfied, there is little point in restricting one's vision to what in fact will turn out to be a perpetuation of the *status quo*. The thought behind our model is that modern societies must learn to examine the implications of different rates of growth, make up their collective mind about what they are going to try to achieve and only then interest themselves in forecasts.

THE CONDITIONS OF THE MODEL

The model is governed by three conditions. First, it must have a framework in which every transaction in the economic system appears, not necessarily in detail but at least in broad aggregates. This need can be met by working within an accounting framework similar to that which underlies the Blue Books on national income and expenditure.

Second, the model must contain numerical estimates of the technical and behavioural relationships which run between production, consumption and accumulation in Britain, and between Britain and the rest of the world. The definition and measurement of these relationships is a matter partly of economic theory, partly of econometric investigation, and partly of good sense and guesswork.

Third, the model must be convertible into a computing programme so that the equations expressing the accounting, technical and behavioural relationships can be solved either simultaneously or iteratively, depending on circumstances, and solved not once but many times according to the different assumptions to be examined.

Our tactics have been to start with a model which takes relatively full advantage of the data available and of the capacity of the Cambridge computer (EDSAC) but uses relationships of a fairly simple form. These can then be gradually improved as our data, theory and computing capacity improve with time and experience.

THE INITIAL MODEL

In order to make the description of our work easier to follow, the initial model is set out schematically in the accompanying diagram. This diagram represents the economic system in terms of the relationships used in the computing programme. It is divided into three parts: the dotted lines for the data; the solid lines for the calculations which constitute the model itself; and the dashed lines for those financial flows which, depending more on patterns of spending and saving than on productive activity, are ignored at this stage, although eventually they will have to be studied in detail. The model develops horizontally from left to right, with two main loops—one involving foreign trade and the other the requirements of the productive system for capital goods. The squares enclose variables—the smaller ones scalars, the larger ones vectors. The circles enclose relationships. The triangle at the top represents the outside world.

The model starts with calculations on the components of final demand, that is to say, all the goods and services to be delivered by the productive system for (i) consumption, (ii) export and (iii) investment. The initial data on these components are collected and processed as follows.

Beginning with consumption, a figure is assumed and shown in the scalar **C**. This figure is then passed through a set of relationships contained in the circle labelled **demand functions**, which sorts out the main categories of consumer goods and services. The constituents of private consumption are estimated in the light of past experience and of observed trends in purchasing habits at different levels of income. The constituents of government consumption are less easy to assess; administration, health or education may be expected to change in a fairly predictable

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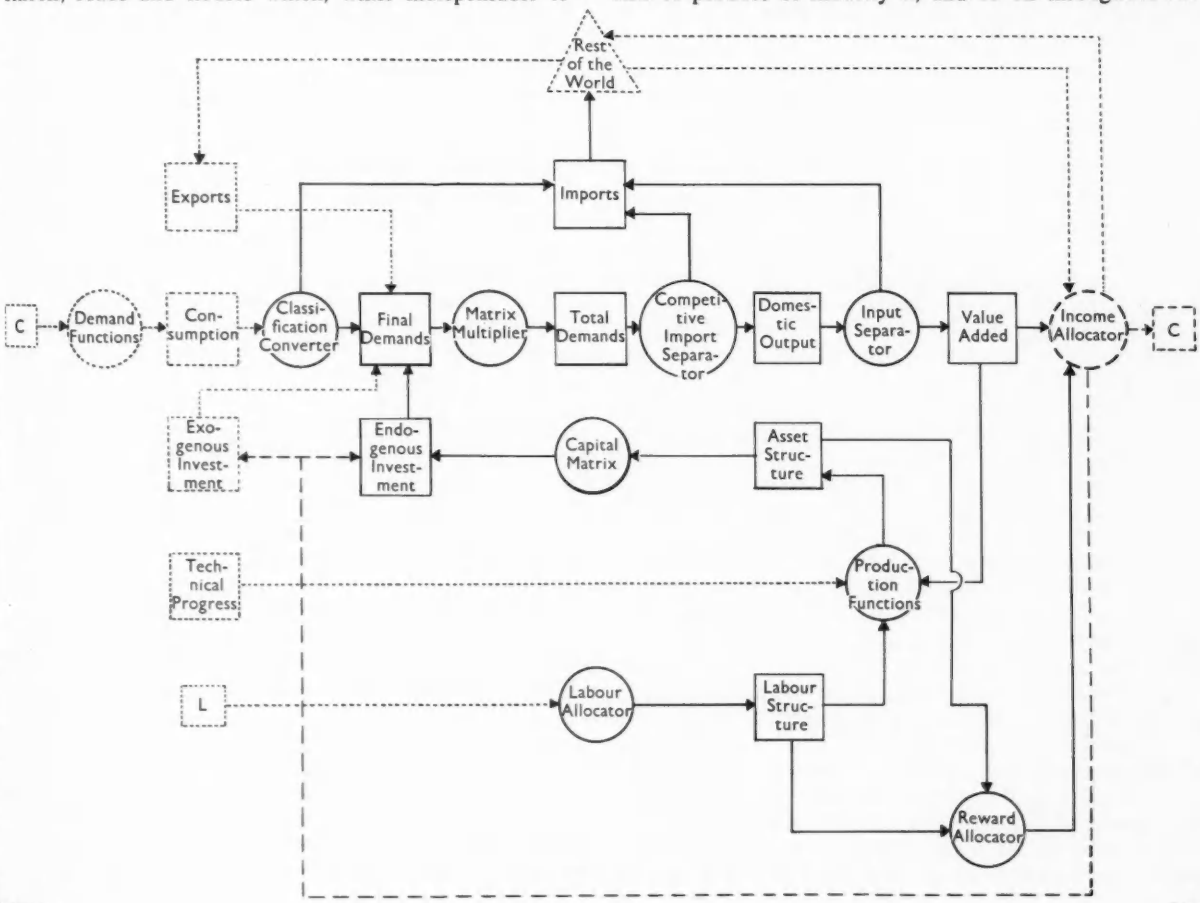
way, but defence, for instance, can only be handled by making alternative assumptions corresponding to different hopes and fears about the state of international tension. These estimates form the vector labelled **consumption**, the elements of which are listed under one of two headings: commodities for private expenditure, purposes for government expenditure. This vector then passes through the **classification converter**, where that part of consumption which can only be satisfied by complementary foreign products such as wine or tropical fruit is diverted off the main stream of the model, since it is outside the scope of domestic production, and channelled into the vector of **imports**; the rest gets rearranged into a classification which specifies what demands each category of consumption makes on the various domestic industries. Thus we have obtained the principal component of the vector labelled **final demands**.

The second component, **exports**, is estimated by examining trends in world trade in those categories of goods which Britain exports and trends in Britain's share in these totals.

The third component, investment, falls into two categories: **endogenous investment**, the new capital goods needed to maintain and increase the country's stock of productive equipment employed in the different industries, and **exogenous investment**, those capital goods, such as schools, roads and houses which, while indispensable to the life of the community, are not obviously and closely tied to industrial levels of production. The demands on industry which arise from these two forms of investment are at this first stage only pencilled in on the basis of past experience. Eventually the vector of exogenous requirements can be modified according to the financial resources produced by the system. As for the endogenous requirements, their exact composition and quantity will be automatically generated by the model itself; hence their position in a solid square.

Unlike the estimates of consumption, those of exports and of investment can be directly drawn up according to an industrial classification and can thus be fed into the vector of **final demands** without any preliminary processing.

When all the data have thus been assembled, the demands on industry are passed through a set of inter-industry relationships labelled **matrix multiplier.** By means of this matrix it is possible to estimate the amount of intermediate products required by the various industries in order to satisfy final demand. For instance, to produce a car we must have parts made of metal, wood, rubber, glass, etc.; to produce these parts we must have the appropriate materials, and so on in a convergent infinite series. Now, if we know that the element a_{jk} of a square matrix A denotes the amount of product of industry j required per unit of product of industry k, and so on throughout the



matrix, then by pre-multiplying the vector of final demands by the matrix inverse $(I-A)^{-1}$, where I is the unit matrix, we can obtain the total of what the economic system requires, including both final and intermediate demands.

The matrix A, which is an important element in the specification of an industrial system, is built up from statistics of inputs and outputs such as those provided for certain industries by the Census of Production. But in using these statistics it must be remembered that while many input-output coefficients change comparatively little in a decade, others change considerably. Thus, for instance, the amount of coal consumed in generating a unit of electricity will in all likelihood continue to fall as improved technology in new power stations replaces the obsolete technology of the old ones. Since what is wanted is a matrix multiplier that reflects the technology of 1970 rather than that of the 1950s, every effort must be made to take such trends into account.

Having obtained the vector of **total demands** from the **matrix multiplier**, it is necessary to consider how far these demands, whether direct or indirect, should be met by domestic production and how far by imports. Complementary imports of consumer goods which cannot be produced in this country were syphoned off at the outset by the **classification converter**, but there is a considerable amount of both final and intermediate products which are imported even though they could be produced at home; examples of this are steel, bacon and knitwear. These are called competitive imports and they are estimated at this stage in the model by reference to some simple consideration such as the trend of imports in the supply of each type of product. At a later stage, these estimates may have to be modified to fit the balance of payments, and later still it should be possible to introduce some optimising principle into the calculation.

Competitive imports are removed from **total demands** and fed into the vector of **imports** by the **competitive import separator**. At the same time, the intermediate products necessary for their production drop out and we obtain the vector labelled **domestic output**, which sets out the level of total output required of each industry at home.

It is now possible to convert the concept of output into a concept of input and to calculate what inputs, both intermediate and primary, each industry needs or, in other words, what costs it must incur in order to produce the final product required of it.

The first step is to subtract the cost of the raw materials which must be bought abroad because they cannot be produced at home, materials such as copper, rubber and crude oil. This second group of complementary imports is removed from **domestic output** and fed into the vector of **imports** by the **input separator**.

At this point we may consider the circuit connecting the productive system with the rest of the world *via* exports and imports. The two dotted lines running between the **income allocator** and the **rest of the world** indicate the net flows of income and capital to and from abroad, and their algebraic sum represents Britain's export surplus. If exports are fixed and a certain sum assumed for the export surplus, then it is possible to work out the total sum available for imports. If this differs from the value of the import requirements estimated so far, it will be necessary to adjust imports so as to bring payments abroad in balance with receipts from abroad. Now, complementary imports of consumer goods are a small item and thus offer little scope for adjustment; complementary imports of raw materials are dictated by the level of domestic output and thus cannot easily be altered; therefore the brunt of the adjustment is borne mainly by competitive imports. The calculation, with its repercussions, can be made by cycling round the loop connecting imports and domestic output until all the flows into and out of the rest of the world are in balance.

Having determined the levels of domestic output and of imports and removed by the **input separator** all intermediate inputs from abroad, the next step is to subtract from each industry the cost of the intermediate inputs it buys at home. This too is done by the **input separator** and the result is a vector of net output or **value added.** The value added in an industry is the excess of the value of its total output over the value of all the intermediate products it has used and processed. Apart from the element of indirect taxes, which goes straight into the **income allocator**, the main part of value added arises from the contributions of the factors of production, essentially labour and capital. These contributions are called primary inputs, and the different ways in which they can be combined to produce the output required, taking into account a certain rate of technical progress, are expressed by a set of relationships called **production functions**.

Output, labour, capital and technical progress are interdependent; if three are fixed, they determine the size of the fourth. In the initial model, **technical progress** is estimated from recent trends in productivity in each industry and appears in the diagram as a separate vector of data, though in practice its realisation is largely connected with the use of up-to-date plant and equipment and could not be achieved without new investment.

The labour available is estimated from demographic projections modified by expected changes in working hours and in social factors affecting the willingness to work. The total of labour is shown in the scalar **L**, distributed among the different industries by the **labour allocator** and set out in the vector of **labour structure**. The **labour allocator** is set to reflect present trends in the distribution of the labour force but can be altered at will and could eventually be elaborated to show how the distribution of the labour force could be improved.

We are now in a position to find out from the **production functions** how much capital equipment is needed in each industry. This is set out in the vector labelled **asset structure.** The **asset structure** goes into the **capital matrix**, which performs the following operations: first, it finds out the difference between the levels of assets required in 1970 and the levels existing in the base period, 1959; second, it turns these increases into annual rates of capital expansion in each industry; third, from these it works out the amount of assets that must be added in each industry (*a*) to carry the same annual rate of expansion into 1971 and (*b*) to replace the assets that are outdated or actually worn out; and

finally, it converts these new requirements into a vector of demands on industries producing capital goods and thus brings us back to **endogenous investment** and closes the second loop of the system. The figure we had pencilled in at the outset for endogenous investment may now turn out to have been wrong, so we must change it in the light of what we have learnt, start again with a revised vector of final demands and cycle round the loops, first balancing the account with the rest of the world, then generating a new set of endogenous investments, and so on until the whole process converges.

We can thus obtain a solution which is technically feasible. It will imply a certain structure of labour and assets in the different industries, and these quantities, when fed into the **reward allocator** which assumes that each factor is paid the value of its marginal product as determined by the production functions, will deliver a stream of income which joins with indirect taxes and income from abroad to be disposed of through the **income allocator**.

This allocation will take essentially three forms: spending on consumption, financing domestic investment and lending abroad. Net lending abroad has already been taken as a datum and shown as a dotted line flowing from the **income allocator** to the **rest of the world**. The other two flows of finance are indicated by dashed lines, since the allocation of income is not an explicit part of the model. It is always possible that the model will give a result which does not agree with the way in which the community normally uses its income. In this case it is up to the community itself to decide whether it prefers to sacrifice its habits to its aims or its aims to its habits.

TRANSIENT AND STEADY STATES

From the account that has just been given it will be seen that the model works out the implications of an assumed rate of growth under steady-state conditions. Although these calculations will not tell us how to reach the steady state, they nevertheless come first, because there is no point in tackling the more difficult problem of finding a transient path until we have found a steady state which we would wish to maintain. If a high rate of increase in consumption is asked for, then a high rate of endogenous investment will be generated by the model, and this in its turn might imply too high a rate of saving. Now, while we need not be governed by existing saving habits and while it is no doubt possible to encourage saving by appropriate financial policies, it is not desirable to do so beyond a certain limit, since this would mean sacrificing the present generation to the future just as an unduly low rate of saving would mean the opposite. Accordingly, our first task is to work out a rate of growth which in the steady state will achieve an acceptable balance between spending and saving, and also a sensible division of saving between endogenous and exogenous investment.

The model is set up in terms of 1970 because it is assumed that, once an acceptable steady state has been found, the transient difficulties can be overcome in the course of a decade. Even if this assumption were wrong, the period of adjustment should not last much longer. Of course, if we aim only at a moderate increase in the rate of growth it may be expected that the transient problems will not prove too difficult, but as we make our aims more ambitious, these problems will increase and may involve longer delays. These questions must, however, be left aside until the steady-state position has been explored.

FURTHER PROBLEMS

As I have said, the forms of the relationships in the initial model are very simple and there is plenty of scope for improvement. Theoretically, one can often see how an improvement could be achieved, but obtaining the necessary data and solving the computing problems is, in practice, far from easy. For example, relative prices could be introduced into the demand functions, but this would require many more data and make the demand functions very complicated; it will only be worth attempting if the model leads us to expect substantial changes in relative prices.

The model also lends itself to programming techniques which would make it possible to work out optimal solutions in certain parts of the system, as I have indicated when discussing imports. If we want to grow faster, we must eventually learn to use our resources to the best advantage and not let their conventional allocation, which in many cases may be very wasteful, pass unchallenged.

Equally important is it, perhaps, to examine some of the technical, social and psychological factors that influence the economic system. Thus it is the general experience all over the world that the increase in a country's output cannot be wholly explained in terms of the inputs of labour and capital; there is always a residue which is usually attributed to technical progress. This may seem very obvious, but what technical progress itself depends on is not so obvious. Is it a question of more scientists in industry and, therefore, a matter of more scientific and technical education, or is it a question of more business men being interested in what scientists have to say, and thus a matter of more education of a different sort? Then again, we find powerful tendencies towards restrictive practices in all walks of life. Perhaps the gains from getting rid of these would greatly exceed the losses; in any case, they want looking into. If we are to make a concerted effort to speed up economic growth, we are bound to view with a critical eye the social forces that seem to oppose this effort and try to establish a better balance between the conflicting claims of progress and security.

CONCLUSION

Our model rejects the notion of a set of cut-and-dried forecasts and tries to establish instead a means whereby economic growth problems can be studied co-operatively on a wide range of assumptions. I emphasise co-operation because there is no royal road to economic success and the practical usefulness of this model depends quite as much on a knowledge of likely technical developments in different industries and of likely responses in the sphere of social habits and attitudes as on matters which lie within the normal professional competence of economists and statisticians, and quite as much on the good will of "capital" and "labour" as on the efficiency of "progress".

TABLE OF ARTIFICIAL EARTH SATELLITES

Compiled by the Royal Aircraft Establishment, Farnborough

NOTES: Dates are given in days and decimals of a day U.T. Payload = weight of instruments. 1 n.m. (nautical mile) = 6080 ft. = 1·853 km. Perigee and apogee heights are over an earth of radius 3442 n.m.
It is not known whether *Discoverer I*, launched February 28, 1959 achieved orbit; it was, nevertheless, designated 1959β.
The designation of the nine pieces of *Sputnik IV* in that adopted in the United States. Russian and British prediction centres refer to *Sputnik IV* as «2 and the rocket as «1. Between 1960 May 15·0 and May 19·0 satellites 1960«1 and 1960«3 were one piece, whose orbit was similar to that of 1960«2.
1960«4 and 1960«5 are believed to be hemispherical shells 26·5" in diameter and 12 lb. in weight—the two halves of the spherical magnesium container that carried the folded sphere into orbit.
1961ß3 and 1961ß4 are the two pieces of the container which carried the folded sphere into orbit.

Name	Launch date	Lifetime	Descent date	Shape and weight	Size	Date of orbital data Determination	Orbital inclination (deg.)	Nodal period (min.)	Perigee (n.m.)	Apogee (n.m.)
Discoverer VI 1959ζ	1959 Aug. 19·81	62 days	1959 Oct. 20·8	Cone-cylinder, 1st day 1700 lb. then 1400 lb.	19′ long 5′ dia.	1959 Aug. 19·81 1959 Sep. 28·2 1959 Oct. 12·7	84 84 84	95·27 92·00 90·00	113 107 100	459 293 194
Vanguard III 1959η	1959 Sep. 18·22	150 yrs.	—	Rocket-sphere-rod, 100 lb. Payload, 50 lb.	8′ long 20″ dia.	1959 Sep. 18·23 1960 Dec. 3·1	33·35 33·34	130·0 129·9	276 274	2020 2012
Lunik III 1959θ	1959 Oct. 4·1	6 months	—	Ellipsoid, 614 lb.	4·3′ long 3·9′ dia.	1959 October	75	22,300	22,000	254,000
Explorer VII 1959ι1	1959 Oct. 13·65	25 yrs.	—	Double cone, 91·5 lb.	30″ long 30″ dia.	1959 Oct. 13·65 1960 Dec. 4·8	50·31 50·31	101·28 101·15	300 300	586 580
Explorer VII rocket 1959ι2	1959 Oct. 13·65	12 yrs.	—	Cylinder, 13 lb.	42″ long 6″ dia.	1959 Oct. 13·65 1960 Nov. 9·9	50·30 50·30	101·25 101·01	298 298	586 574
Discoverer VII 1959ι1	1959 Nov. 7·85	19 days	1959 Nov. 26·8	Cone-cylinder, 1st day 1700 lb. then 1400 lb.	19′ long 5′ dia.	1959 Nov. 15·6 1959 Nov. 15·6 1959 Nov. 20·8	82 82 82	94·70 92·9 91·5	87 84 82	455 364 292
Discoverer VIII 1959λ	1959 Nov. 20·81	108·2 days	1960 Mar. 8·05	Cone-cylinder, 1st day 1700 lb. then 1400 lb.	19′ long 5′ dia.	1959 Nov. 20·81 1960 Jan. 15·5 1960 Feb. 29·5	81 81 81	103·72 98·00 92·00	100 96 88	906 618 312
Tiros I 1960ß2	1960 Apr. 1·49	50 yrs.	—	Cylinder, 270 lb.	19″ long 42″ dia.	1960 Apr. 1·49 1960 Nov. 30·5	48·4 48·4	99·16 99·14	372 372	406 406
Tiros I rocket 1960ß1	1960 Apr. 1·49	20 yrs.	—	Cylinder, 50 lb.	4′ long 20″ dia.	1960 Apr. 1·49 1960 Dec. 7·4	48·4 48·4	99·15 99·10	372 372	406 404
Transit 1B 1960γ2	1960 Apr. 13·50	2 yrs.	—	Sphere, 267 lb.	36″ dia.	1960 Apr. 13·50 1960 Dec. 7·0	51·28 51·28	95·81 95·24	207 206	397 368
Transit 1B rocket 1960γ1	1960 Apr. 13·50	14 months	—	Cylinder, 1000 lb.	178″ long 55″ dia.	1960 Apr. 13·50 1960 Dec. 8·6	51·25 51·25	95·25 93·21	172 154	403 314
Transit 1B fragment 1960γ3	1960 Apr. 13·50	3 months?	—	Disc —	1″ long 8″ dia.	1960 Apr. 13·50 1960 June 1	51·3 51·3	94·78 93·0	158 150	394 306
Discoverer II 1960δ	1960 Apr. 15·85	10·9 days	1960 Apr. 26·7	Cone-cylinder, 1st day 1700 lb. then 1400 lb.	19′ long 5′ dia.	1960 Apr. 16·86 1960 Apr. 24·7	80 80	92·16 89·75	90 85	318 195
Sputnik IV 1960ε1	1960 May 15·00	1½ yrs.	—	— 2 tons ?	— —	1960 May 19·0 1960 Nov. 7·0	65·0 65·0	94·25 93·53	156 153	364 331
Sputnik IV rocket 1960ε2	1960 May 15·00	63·8 days	1960 July 17·8	Cylinder ? —	— —	1960 May 15·00 1960 June 8·01 1960 July 15·55	64·9 64·9 64·9	91·25 90·79 88·69	164 154 110	198 184 118
Sputnik IV cabin 1960ε3	1960 May 15·00	2½ yrs.	—	— 2½ tons ?	— —	1960 May 19·0 1960 Nov. 10·5	64·9 64·9	94·27 93·85	151 149	371 351
Sputnik IV casing 1960ε4	1960 May 15·00	15 months?	—	— —	— —	1960 May 19·0 1960 Nov. 8·5	64·9 64·9	94·28 93·5	156 153	366 329
Sputnik IV casing 1960ε5	1960 May 15·00	4 months?	—	— —	— —	1960 May 19·0	64·9	94·32	157	367
Sputnik IV casing 1960ε6	1960 May 15·00	4 months?	—	— —	— —	1960 May 19·0 1960 June 2·0	64·9 64·9	94·36 94·07	154 154	372 358
Sputnik IV casing 1960ε7	1960 May 15·00	132 days	1960 Sep. 24	— —	— —	1960 May 19·0 1960 June 6·0	64·9 64·9	94·38 94·00	156 156	372 352
Sputnik IV casing 1960ε8	1960 May 15·00	4 months?	—	— —	— —	1960 May 19·0	64·9	94·40	156	372
Sputnik IV casing 1960ε9	1960 May 15·00	4 months?	—	— —	— —	1960 May 19·0	64·7	94·41	151	377
Midas II 1960ζ1	1960 May 24·73	10 yrs.	—	Cylinder. 5000 lb.	22′ long 5′ dia.	1960 May 24·73 1960 Oct. 27·1	33·00 33·00	94·44 94·36	260 259	276 273
Midas II nose-cap 1960ζ2	1960 May 24·73	194·5 days	1960 Dec. 5·3	— —	— —	1960 May 24·73 1960 Oct. 9·5	33·00 33·00	94·44 93·0	260 226	276 236
Transit IIA 1960π1	1960 June 22·25	60 yrs.	—	Sphere, 223 lb.	36″ dia.	1960 June 22·25	66·77	101·66	338	566
Greb 1960π2	1960 June 22·25	40 yrs.	—	Sphere, 42 lb.	20″ dia.	1960 June 22·25	66·77	101·66	332	572
Transit IIA rocket 1960π3	1960 June 22·25	30 yrs.	—	Cylinder, 1000 lb.	178″ long 55″ dia.	1960 June 22·25	66·77	101·37	333	555
Discoverer XIII 1960σ	1960 Aug. 10·86	96 days	1960 Nov. 14·9	Cone-cylinder, 1st day 1700 lb. then 1400 lb.	19′ long 5′ dia.	1960 Aug. 10·86 1960 Oct. 9·9 1960 Nov. 9·4	83 83 83	94·04 92·00 90·00	139 133 122	369 267 172
Echo I 1960ι1	1960 Aug. 12·40	2 yrs.?	—	Inflated sphere, about 150 lb.	100′ dia.	1960 Aug. 12·40 1960 Nov. 5·6	47·2 47·3	118·2 117·8	822 610	910 1100
Echo I rocket 1960ι2	1960 Aug. 12·40	4000 yrs.?	—	Cylinder. 50 lb.	4′ long 20″ dia.	1960 Aug. 12·40	47·2	118·0	824	896
Echo I fragments 1960ι3–5	1960 Aug. 12·40	—	—	(see note below)		Details unknown				
Discoverer XIV 1960«	1960 Aug. 18·83	28 days	1960 Sep. 16·0	Cone-cylinder, 1st day 1700 lb. then 1400 lb.	19′ long 5′ dia.	1960 Aug. 18·83 1960 Aug. 30·75 1960 Sep. 10·1	80 80 80	94·55 93·00 91·00	100 98 94	434 354 254
Sputnik V 1960λ1	1960 Aug. 19·4	1·1 days	1960 Aug. 20·5	— 4·5 tons	— —	1960 Aug. 19·4	64·95	90·72	158	176
Sputnik V rocket 1960λ2	1960 Aug. 19·4	35 days	1960 Sep. 23·6	Cylinder ?	— —	1960 Aug. 19·4 1960 Sep. 10·0 1960 Sep. 19·9	64·9 64·9 64·9	90·7 90·0 89·0	158 142 130	176 154 124
Discoverer XV 1960ο	1960 Sep. 13·73	34·2 days	1960 Oct. 18	Cone-cylinder,	19′ long	1960 Sep. 13·73	81	94·23	109	407

Name	Launch date	Lifetime	Descent date	Shape and weight	Size	Date of orbital data Determination	Orbital inclination (deg.)	Nodal period (min.)	Perigee (n.m.)	Apogee (n.m.)
Courier 1B 1960ο2 rocket	1960 Oct. 4·74	250 yrs.	—	Cylinder, 1000 lb.	178″ long 55″ dia.	1960 Oct. 4·74	28·30	106·38	512	638
Explorer VIII 1960ζ1	1960 Nov. 3·22	20 yrs.	—	Double cone, 90 lb.	30″ long 30″ dia.	1960 Nov. 3·22	50·0	112·69	225	1235
Explorer VIII rocket 1960ζ2	1960 Nov. 3·22	10 yrs.	—	Cylinder, 13 lb.	42″ long 6″ dia.	1960 Nov. 3·22	50·0	112·68	225	1235
Discoverer XVII 1960ρ	1960 Nov. 12·86	47 days	1960 Dec. 29	Cone-cylinder, 1st 2 days 2100 lb then 1800 lb.	25′ long 5′ dia.	1960 Nov. 12·86 1960 Dec. 13·75	82 82	96·45 93·0	100 96	534 356
Tiros II 1960π1	1960 Nov. 23·47	20 yrs.	—	Cylinder, 280 lb.	19″ long 42″ dia.	1960 Nov. 23·47	48·5	98·20	336	392
Tiros II rocket 1960π2	1960 Nov. 23·47	10 yrs.	—	Cylinder, 50 lb.	4′ long 20″ dia.	1960 Nov. 23·47	48·6	98·1	328	396
Sputnik VI 1960ρ1	1960 Dec. 1·3	1 day	1960 Dec. 2	— 10,060 lb.	— —	1960 Dec. 1·3	64·97	88·47	90	125
Sputnik VI rocket 1960ρ2	1960 Dec. 1·3	1½ days	1960 Dec. 2	Cylinder ? —	— —	1960 Dec. 1·3	Orbit similar to 1960ρ1			
Discoverer XVIII 1960σ	1960 Dec. 7·85	116 days	1961 Apr. 2	Cone-cylinder —	25′ long 5′ dia.	1960 Dec. 7·85 1961 Feb. 5·75	81·5 81·5	93·66 92·0	124 119	364 281
Discoverer XIX 1960τ	1960 Dec. 20·86	33·2 days	1961 Jan. 23·1	Cone-cylinder, 2100 lb.	25′ long 5′ dia.	1960 Dec. 20·86 1961 Jan. 16·6	83·4 83·4	93·00 90·0	111 101	341 193
Samos II 1961«1	1961 Jan. 31·85	—	—	Cylinder —	22′ long 5′ dia.	1961 Jan. 31·9	97·40	94·97	256	298
Samos II nose-cap 1961«2	1961 Jan. 31·85	—	—	— —	— —	1961 Jan. 31·9	97·40	94·97	256	298
Sputnik VII 1961ß1	1961 Feb. 4	22 days	1961 Feb. 26	— 14,293 lb.	— —	1961 Feb. 4	64·9	89·8	114	172
Sputnik VII rocket 1961ß2	1961 Feb. 4	9 days	1961 Feb. 12–13	— —	— —	1961 Feb. 4	64·9	Initial orbit similar to 1961ß1		
Sputnik VII casing 1961ß3	1961 Feb. 4	41 days	1961 Mar. 17	— —	— —	1961 Feb. 4 1961 Mar. 10·6	64·89 64·89	90·2 89·0	125 112	183 132
Venus probe 1961γ1	1961 Feb. 12	—	—	Cylinder, 1419 lb.	— —	Initial earth-satellite orbit similar to 1961γ3				
Sputnik VIII rocket 1961γ2	1961 Feb. 12	6 days	1961 Feb. 18	— —	— —	1961 Feb. 13·9	65·0	89·2	106	148
Sputnik VIII 1961γ3	1961 Feb. 12	14 days	1961 Feb. 25·8	— —	— —	1961 Feb. 12	65·0	89·6	120	151
Sputnik VIII casing 1961γ4	1961 Feb. 12	1–6 days	—	— —	— —	1961 Feb. 12	65·0	Orbit similar to 1961γ2		
Explorer IX 1961ι1	1961 Feb. 16·55	—	—	Inflated sphere, 15 lb.	12′ dia.	1961 Feb. 16·6 1961 Mar. 21·0	38·9 38·9	118·28 118·28	344 360	1392 1376
Explorer IX rocket 1961ι2	1961 Feb. 16·55	—	—	Cylinder, 52 lb.	58″ long 18″ dia.	1961 Feb. 16·6	38·6	118·4	344	1396
Explorer IX fragment 1961ι3	1961 Feb. 16·55	—	—	(see note below)		1961 Mar. 18·9	38·9	118·1	346	1380
Explorer IX fragment 1961ι4	1961 Feb. 16·55	—	—	(see note below)		Probably similar to 1961ι3				
Discoverer XX 1961κ1	1961 Feb. 17·85	1 year	—	Cone-cylinder, 1st 4 days 2450 lb.	25′ long 5″ dia.	1961 Feb. 17·85	80·9	95·4	155	423
Discoverer XX fragment 1961κ2	1961 Feb. 21(?)	37–40 days	Mar. 30–Apr. 2	— —	— —	1961 Mar. 12·8	80·9	93·2	150	302
Discoverer XX fragment 1961κ3	1961 Feb. 21(?)	—	—	— —	— —	1961 Mar. 12·9	80·9	94·0	153	353
Discoverer XX fragment 1961κ4	1961 Feb. 21(?)	—	—	— —	— —	1961 Mar. 13·2	80·9	96·4	213	419
Discoverer XXI 1961ξ	1961 Feb. 18·8	10 months	—	Cone-cylinder, 2100 lb.	25′ long 5″ dia.	1961 Feb. 19·0	80·7	97·85	128	576
Transit 1IIB 1961ν	1961 Feb. 22·16	36·4 days	1961 Mar. 30·54	Cylinder, 1300 lb.	203″ long 55″ dia.	1961 Feb. 22·2 1961 Mar. 26·0	28·38 28·38	96·22 90·67	91 81	541 261
Sputnik IX 1961ο1	1961 Mar. 9	< 1 day	1961 Mar. 9	— 10,360 lb.	— —	1961 Mar. 9	64·9	88·6	95	130
Sputnik IX rocket 1961ο2	1961 Mar. 9	1 day	1961 Mar. 10	— —	— —	1961 Mar. 9·6	64·9	88·2	93	107
Sputnik IX casing 1961ο3	1961 Mar. 9	1 day	1961 Mar. 10	— —	— —	1961 Mar. 9·6	64·9	88·0	Similar to 1961ο2	
Sputnik X 1961π1	1961 Mar. 25	< 1 day	1961 Mar. 25	— 4½ tons	— —	1961 Mar. 25	64·9	88·42	89	125
Sputnik X rocket 1961π2	1961 Mar. 25	2 days	1961 Mar. 27	— —	— —	1961 Mar. 25·9	65·0	87·8	72	103
Sputnik X casing 1961π3	1961 Mar. 25	1½ days	1961 Mar. 26	— —	— —	1961 Mar. 25·6	65·0	88·5	90	128
Explorer X 1961«	1961 Mar. 25·3	—	—	— 78 lb.	— —	1961 Mar. 25	33	6660	94	120,000
Discoverer XXII 1961λ	1961 Apr. 8·8	—	—	—	—	1961 Apr. 9·0 1961 Apr. 12·25	82·3 82·3	94·1 89·1	159 91	350 166

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THE BOOKSHELF

Primitive Man and His Ways

By Kaj Birket-Smith (*Odhams Press, 239 pp., 25s.*). Translated from the Danish by Roy Duffell.

The accounts of six primitive cultures that form the body of this text are set between introductory and concluding chapters which clearly state the author's theoretical interests; he is primarily concerned with "cultural development" and the ways in which this is influenced by "nature". This influence of geographical and human factors on the evolution of culture proceeds in two main ways: through the diffusion of culture traits between peoples, and by adaptation of particular cultural forms to local conditions. "A culture", writes Birket-Smith, "will always be the joint product of the human spirit and the environment."

The six cultures were selected to illustrate how adaptation may occur in the process of development, especially adaptation to differing climatic conditions. This has led to some excellent and some curious choices. The material on the Lapps is rich in detail and the author is able to show how differences in environment, as for instance between coastal and mountain Lapps, are related to the varying use made of the reindeer. The Maori material neatly demonstrates the manner in which the transfer from a tropical to a temperate climate made changes in agriculture and cloth-making necessary, while the Plains Indians are described in the context of the changes brought about by the introduction of the horse. The chapter on the Australian Aborigines is concerned with their ways of utilising a particularly harsh environment, and also with variations among aboriginal groups that are ascribed in the main to the differential diffusion of traits from the north.

In the course of these accounts Birket-Smith introduces a wealth of historical and archeological detail; such detail is virtually inevitable where (as in the treatment of the Lapps, the Australian Aborigines and the Plains Indians) several culturally and linguistically distinct groups are considered together as a unit. Thus we have accounts which emphasize the description of items of material culture, types of totemism, variations of marriage rules and ways of reckoning descent, with little attention to the description of the social organisation of any one group in detail.

Accounts of the Powhatan Indians of Virginia and the Tuareg of the Sahara are fragmentary and give almost no indication of the culture in a viable form. If such partial reconstructions were the only material available to anthropologists we would have to make the best of the situation, but there are now many richly documented studies of living primitive societies. Birket-Smith's sub-title, "Patterns of Life in Some Native Societies" would be more appropriate had these been considered.

E. N. GOODY

Faculty of Archaeology and Anthropology, Cambridge

Principles of Meteoritics

By E. L. Krinov (*Pergamon Press, xi+535 pp., 70s.*)

Meteorites are inherently interesting objects; they come to us out of space, and the phenomena of their arrival are usually spectacular. They are also of great scientific importance, for they are the only form of non-terrestrial matter available to us for direct laboratory study, and any theory of the origin and development of the solar system must account for the known facts concerning them. For these reasons, Prof. Krinov's book may be more widely read than the apparent specialism of its title might lead one to expect.

The study of meteorites is a fertile source of controversy, one of the most hotly debated issues being the existence or otherwise of interstellar bodies. The whole question hinges on the velocities with which meteorites enter the Earth's atmosphere, and this is the very quantity most difficult to measure with sufficient accuracy. Krinov is firmly of the opinion that meteorites are all members of the solar system, and he adduces weighty evidence in support of his view. It is doubtful, however, whether the elliptical orbits he tabulates should be accepted any more readily than the hyperbolic orbits derived by other workers from the same observations—what is needed is a body of observational data capable of only one interpretation. It must be said that such few accurate observations as have been made, together with statistical and indirect evidence, are all in favour of the asteroidal nature of meteorite orbits, and this reviewer fully agrees with the author's conviction that meteorites and asteroids are genetically related.

We have much to learn before the question of the origin of meteorites can be finally settled. That they have been produced by the fragmentation of a much larger body or bodies can hardly be doubted, and from the orderly progression of meteoritic structure and composition so clearly described and exemplified in this book, the conviction steadily grows that as we sample rocks from greater and greater depths below the surface of our own planet, we shall find them resembling more and more closely the specimens in our meteorite collections. In particular, we may find that the puzzling chondritic structure of most stony meteorites is present in the rocks of the Earth's mantle below the crust. We already have strong reasons for believing that the Earth's core is composed of nickel-iron similar to that of the iron meteorites.

The section devoted to the mineralogy

of meteorites is particularly good, and would stand on its own as a valuable contribution to the literature of meteoritics. A notable advance in this field is the identification of hydrated silicates, hitherto unknown in meteorites, and probably of metamorphic origin. Nothing is said about the presence or otherwise of organic compounds, nor are hydrocarbons mentioned other than methane. One suspects that the author is rightly sceptical of some of the wilder claims to the discovery of material of organic origin in meteorites.

Prof. Krinov devotes much space to the morphology of meteorites, and has elaborated a system of classification of surface structure from which a purely superficial examination may be made to yield a great deal of information about the atmospheric flight of a given specimen. It is argued that the smaller sizes of stony meteorites compared with the irons are not due, as Ninninger and others have suggested, to the greater friability of the former resulting in more extensive fragmentation in the atmosphere, because the total weight of even the largest stony showers is much less than the larger iron masses, and the latter often arrive in showers, as in the case of the Sikhote-Alin fall.

Although the fall of the great Tunguska meteorite of 1908 is, of course, treated at some length; the author had not at the time of writing developed his ideas as to its nature: readers may know that he has more recently suggested—as have others—that the body was the nucleus of a comet, and that it was moving in a retrograde orbit. If we assume that the nucleus of a comet consists of a mass of ices of various gases interspersed with solid particles, as conceived by Whipple, many of the unusual features of this immense and catastrophic event would be explained, but at this stage the theory cannot be regarded as more than an interesting and possibly fruitful idea. The U.S.S.R. has been favoured with the two greatest recorded falls of meteorites, and the less massive but vastly more informative fall at Sikhote-Alin in 1947 is fully described. This shower of seventy tons of iron meteorites has probably added more to our knowledge of meteorites than any other single event since the stony shower of 1803 at L'Aigle finally induced the French Academy of Sciences to recognise what untutored peasants had known for thousands of years: that stones do fall from the sky.

Tektites are dealt with rather summarily, which is a pity, for the study of these controversial objects has reached a stage where a comprehensive treatment of our knowledge and ideas concerning them, written with the care and authority of the author, would be very useful.

This book is a welcome and valuable addition to the growing list of English translations of Russian scientific works. The language barrier has been as great a hindrance to our appreciation of Soviet science as its political counterpart, and the publishers deserve our gratitude for making this volume available at a price which in the circumstances is almost charitable.

H. B. RIDLEY

Meteor Section,
The British Astronomical Association,
London

Beaches and Coasts

By Cuchlaine A. M. King (*Edward Arnold, 403 pp., 65s.*)

Coastal Changes

By W. W. Williams (*Routledge and Kegan Paul, 220 pp., 28s.*)

When D. W. Johnson published his great book in 1919, his interest in coastal subsidence led him to enquire into the fundamental principles of shore processes and shoreline development; he also included a digest of all the coastal literature he had read, even if not peculiarly relevant to his subject in order "to render a service to my fellow students".

Dr King, who has surely published the most notable book on world-wide coastal studies since the appearance of Johnson's book, has performed a similar amiable service. The aim of the book is "to gather together some of the recent work on coastal problems, especially those associated with the character of the beach".

It would be impossible to expect any book to be comprehensive, but Dr King's book is very nearly so, as is shown at the ends of the chapters by the bibliographies which elaborate her descriptions of the three means of approach to coastal studies—theoretical, the use of models and field observations. She describes with clarity much of the model work conducted since the war in the United States of America and in England.

Miss King's own field observations appear in their proper place and there are careful accounts of observations and experiments on beaches and water movements by other workers in many different countries.

The comparative studies of different theories, such as those of wave generation and wave forecasting, are impressive. It is agreeable and surprising to find a geographer who understands the mathematics involved and who is able to summarise the arguments so succinctly and assess the possible values as related to coastal studies

The chapters are very well laid out and the precise summaries of the different sections are particularly valuable in a reference book such as this. This systematic lay-out compensates for a style of writing which is not invariably felicitous.

The first chapter deals with factors which affect the character of the beach, that is, the material of which it is composed and a general statement of the influences on this material, waves, tides and wind. Chapters 3, 4, 5, and 6 are concerned with details of modern studies on waves and wind action and the always changing physical shape of the beach. A preamble to this is the description in chapter 2 of the methods used in the work, particularly models and field observations. Dr King's crisp and assured dealing with nomenclature is very welcome.

Classifications of beaches and coasts occupy the middle portion of the book. A comparative study of those by Johnson, Shepard, Cotton, and Valentin is made in chapter 7 with the conclusion that none of them is completely satisfactory. (It is difficult, though, to be convinced that any such classification is of value except as an interesting excursion into orderliness.) Valentin's distinction between advancing coasts and retreating coasts is the one which finds most favour with Dr King and forms the basis of the next two chapters, dealing first with positive action, the accumulation of beaches and outward building of coasts, and second with the destructive action of the sea and coastal erosion. Having considered all the influences, it is possible for Dr King to describe the beach gradient and beach profiles in further detail in chapter 10.

A short chapter on historical evidence emphasises the caution with which it must be interpreted and the final chapter is an attempt to discuss coastal development. The author realises that the unique nature of any particular strip of coast makes this difficult and that although both steep, indented cliff coasts and flat coasts tend to become straight—the one by erosion and the other by accretion—the final stage in the cycle of marine erosion does not appear anywhere in the world today because the sea-level has oscillated too frequently in recent times.

Dr King has accumulated a mass of information and presented it in a book which is exceptionally well laid-out and with an exposition of great clarity. It is a book which many people of diverse interests—engineers, oceanographers, geo-

logists and geomorphologists—will be pleased to possess.

Unfortunately the same cannot be said of Mr Williams's book. In his agreeable introduction, he states that it is written ten years later than it might have been and that it is not a treatise of new methods but rather a brief statement of present coastal work with an opinion as to future work. With this caution, and in a book of this nature and length, one is prepared for selected omissions, but this book is considerably out of date. Since 1947, when Sverdrup and Munk published *Wind, Sea and Swell: Theory of Relations for Forecasting*, a report which is used by Mr Williams, there have been great advances in the theories of wave generation by Eckart and Phillips and wave forecasting by Roll, Bretschneider, Neumann and Fischer, and by Darbyshire in this country; none of these names are mentioned by Mr Williams. On pages 47 and 48 there are descriptions of wave heights as estimated by Vaughan Cornish and various ships' officers. It seems a pity that these estimates were not supplemented by more recent and more accurate measurements of wave heights.

The work on beaches in the United States of America is insufficiently mentioned. Much has been published from the Institute of Engineering Research at Berkeley, California, and although Mr Williams is acquainted with the Technical Reports of the Beach Erosion Board, there are many further relevant publications such as the Technical Memoranda to which he does not refer.

These omissions are the more disappointing as the generally naïve style allows for lengthy explanations and descriptions. The form of the book is promising, first describing the geological factors which have affected the coastal features, then the agents which have worked on this material to change the coastline by erosion, transport and deposition, and lastly the evidence of changes and the observational methods used. Dr King is a former pupil and co-worker of Mr Williams and in this last section his book could have formed a useful complement to Dr King's book.

Mr Williams's bibliography is untidily presented; most of the publications are undated, several of the authors have no initials, some of the references are incomplete or erroneous, and the use of italics and abbreviations is spasmodic.

M. SWALLOW

National Institute of Oceanography, Wormley

Hydrodynamics of Oceans and Atmospheres

(*Pergamon Press, 1960, xi+290 pp., 63s.*)

This inadequate volume underlines the unsatisfactory state of modern theoretical meteorology and oceanography much more clearly than any "adequate" textbook could possibly have done. The contents do not have the generality implied by the title but are apparently limited to topics amendable to the techniques used in atomic theory. The approach is that of a pure mathematician grappling with the abstract concept of a fluid in a gravitational field, deliberately not drawing on observations of the ocean or atmosphere in order to test his conclusions.

In fact, the author warns us in Chapter I that his objective is "to illustrate the laws of dynamics, rather than to imitate nature". Personally, I fail to see the distinction, unless the laws referred to are rather fundamental and usually associated with the work of Newton in his endeavour to "imitate nature". For example, the first section of the book is concerned with the state of no motion—a fluid in hydrostatic equilibrium. However, the model atmosphere in which the temperature is assumed to decrease linearly with height (as in the lower atmosphere) is condemned as leading to the "unnecessary"

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paradox of fluid at zero temperature. The fact is that such a model atmosphere is a very good approximation to the state of the lower atmosphere and useful for the interpretation of motions which are confined to that region. This somewhat trivial example—for the author is aware of the temperature structure of the atmosphere and the point is rather one of emphasis—illustrates that in the conflict between mathematical elegance and working model, the elegance has the deciding vote.

If any mathematician is lured into the field by this volume he must have a rude awakening, for the subject as it stands is much less pure-mathematically satisfying and much more interesting. If this book goads any of the top-line theoretical meteorologists into writing a full, up-to-date account of his subject, then the author's labour will have been fully justified. J. S. A. GREEN

Department of Meteorology, Imperial College of Science and Technology, London University

Quantum Mechanics

By J. L. Powell and B. Crasemann
(*Addison-Wesley, 495 pp., 74s.*)

The number of elementary texts on quantum mechanics is now legion. Among these, the number of good ones is also fairly large. Powell and Crasemann is essentially a good elementary text but it differs so little from some of its predecessors that I do not know if a new book was really warranted. However, among its special merits are the emphasis on the role of symmetry operations and the essentially algebraic structure of quantum mechanics (though, unhappily the authors—like most of their American colleagues—fight shy of Dirac's notation). The Addison-Wesley printing is, as usual, a pure delight, though the price is not. The number of problems is vast and varied. For those who are by now just tired of the standard elementary texts, Powell and Crasemann can be strongly recommended. A. SALAM

Imperial College, London

Theory of Markov Processes

By E. B. Dynkin
(*Pergamon Press, 210 pp., 60s.*)

This monograph is on the mathematical foundations of Markov processes and is intended for readers with considerable mathematical equipment.

Markov processes were introduced at the beginning of this century. They can be described roughly as follows. Consider a particle moving in space. The motion is random and only the distribution functions of its co-ordinates can be found. We suppose that if the position of the particle at time t_1 is known then we can find certain distribution functions for its position at time t_2 where $t_2 > t_1$. These will depend on its position at time t_1, but no further information about its movement prior to time t_1 will enable us to improve our knowledge of its motion. In this sense its future motion depends on its position at time t_1 but is independent of its motion up to this time.

The processes originally considered by Markov and other investigators in the early part of this century corresponded to observations at discrete unit intervals of time and the number of positions which the particle could assume were either finite or at most countable. Such a theory has the advantage of mathematical simplicity. In some circumstances, it provides a reasonable approximation to an actual physical state, but it is open to many objections. However, as soon as we leave processes in discrete time and consider processes in continuous time we run into some serious mathematical difficulties. The first satisfactory theory of this general case was given by Kolmogoroff in 1938. A further treatment of this subject within the general framework of stochastic processes was given by Doob in 1957. Here a new element was introduced. Our elementary particle may not only be subject to random motion, but it may be liable to having its motion terminated at some instant, for example, by collision with another particle or with the wall of the container. The instant of cut-off is itself a random variable.

Dynkin's definition of a Markov process is designed to overcome the mathematical difficulties connected with the measurability of sets in the space of events and also to allow for the finite life of the particles. It is too complicated to give here, but the author's aim is to develop a theory independent of the general theory of stochastic processes.

The monograph contains a thorough investigation of sub-processes; these are processes which can be obtained by shortening the life in a given Markov process. This is a theory which has been developed by the author and his pupils. The author then reconsiders the question of the independence of past and future in a Markov process and this leads to the concept of a strictly Markov process, a concept introduced by Doob and the author. A final chapter discusses the trajectories of a given process and gives conditions for a process to have continuous trajectories, bounded trajectories or for it to be of a jump type—that is, the variables are constant except for a countable number of instants where they have simple discontinuities.

This monograph is a most valuable contribution to the subject. It is clearly written, but the style is condensed and calls for careful reading. It is provided with a useful index of technical terms, many of which are introduced here for the first time. A. C. OFFORD

Department of Mathematics, Birkbeck College, London

The Inheritors

By Ritchie Calder (*Heinemann, 336 pp., 25s.*)

This book describes Man's scientific achievements from the earliest times and takes a look into the future. Its style is reminiscent of H. G. Wells's "Outline of History".

Nerves, Brain and Man

By John Grayson (*Phoenix, 243 pp., 25s.*)

A readable elementary book about the nervous system as seen by the anatomist, the physiologist, and the electronics physicist. The author is Professor of Physiology at University College, Ibadan, Nigeria.

Boolean Algebra and its Applications

By J. Eldon Whitesitt (*Addison-Wesley, 182 pp., 51s.*)

This book offers an introductory treatment of Boolean algebra for the reader with a limited formal mathematical background. Written for a one-semester course for students of mathematics and engineering, the book was also designed to serve as a reference for scientists and engineers concerned with computer design, control systems and electronic circuitry.

The Hidden Life of Flowers

By J. M. Guilcher (*Oliver and Boyd, 93 pp., 7s. 6d.*)

The fifth volume of the *World of Nature* Series, this book tells the story of the reproductive processes in plants. About three-fourths of the space is used for photographs that amply illustrate the simple descriptions of the various phases of reproduction.

Recent Advances in Soviet Science

(*Todd, 224 pp., 25s.*)

A collection of articles by and interviews with Soviet scientists and officials that have been issued as press releases by the Soviet Embassy in London. It covers such areas as space exploration and astronomy, uses of resources, town planning and education.

Crystals and Crystal Growing

By Alan Holden and Phylis Singer (*Heinemann, 320 pp., 10s. 6d.*)

The Physics of Television

By D. G. Fink and D. M. Luytens (*Heinemann, 160 pp., 5s.*)

The Birth of a New Physics

By I. Bernard Cohen (*Heinemann, 200 pp., 5s.*)

Waves and the Ear

By W. A. van Bergeijk, J. R. Pierce, and E. E. David, Jr. (*Heinemann, 235 pp., 5s.*)

These are four additions to the Science Study Series (Nos. 6 to 9) that are being produced under the aegis of Educational Services Incorporated, a group of physicists, teachers, and individuals working in the various mass media. The Series is intended to cover fundamental topics in physics and the role of physics in technology and is written primarily for the young student and the layman. The gaudy covers should not be taken as an indication of the contents, for the material inside is rather well presented.

Management Training: Aims and Methods

By Patrick Meredith (*English Universities Press, 174 pp., 6s.*)

This book was published to bring some of the results of social theory and management research to those in administrative positions in industry and education.

Principles of Astronautics

By M. Vertregt (*Elsevier, 221 pp., 18s.*)

A survey of the theories and mathematics involved in rocketry and space flight, this book is addressed to the advanced reader who wants to know a little more about astronautics than he can learn from popular science books.

Learning, Remembering and Knowing

By Patrick Meredith (*English Universities Press, 174 pp., 6s.*)

Some novel ideas about studying are presented for the solitary student in this Addition to the *Teach Yourself* series.

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Electron Microscopy—
A Handbook for Biologists

By E. H. Mercer and M. S. C. Birbeck (*Blackwell Scientific Publications, 76 pp., 9s. 6d.*)

A brief and practical set of instructions for biologists who wish to prepare their material for examination in the electron microscope, this book is not a history of the subject nor are all the possible procedures described. The methods given are the best of those current and should prove adequate in most circumstances.

Science and Human Values

By J. Bronowski (*Hutchinson, 96pp., 12s. 6d.*)

This book is the first of three essays that were first given as lectures at the Massachusetts Institute of Technology in 1953 when Dr Bronowski was Carnegie Professor there. "Reading these essays again now, I find little that I would change and a few things I want to add," he writes in the preface.

These essays are an attempt to examine the creative activity of the mind and show that it is a single phenomenon in all fields of mental activity. But one feels on reading it that the author is too much the poet and not sufficiently the probing analyst who is going to remove the accretions of emotion and sentiment that have built up over the years.

Louis Pasteur

By Jacques Nicolle (*Hutchinson, 196 pp., 35s.*)

This detailed account of the scientific methods and major discoveries of Pasteur covers his ten major pieces of research and describes the impact they had on the science of that period.

LETTERS TO THE EDITOR

New Ways of Curing Neuroses

Sir:

I have read Prof. Eysenck's article "New Ways of Curing Neuroses" in your April issue. Some years ago I was psychoanalysed by the late Dr Ernest Jones, with great benefit to myself. I certainly cannot agree that psychoanalysis is valueless. To avoid giving a very one-sided impression to your readers, I suggest that you should invite a psychoanalyst to comment on Prof. Eysenck's article.

R. NORTH

Vortex Down Under

Sir:

My own intensive researches—involving, unfortunately, an excursion no further than my own bathroom—indicated that the direction of rotation depended on nothing more subtle than the foot (right or left) with which I gave a slight encouragement to the departing water before I stepped out of the bath.

R. D. Y. PERRETT

THE PROGRESS OF SCIENCE

(continued from page 183)

with which the lines of the pattern were intersected by a line segment, of fixed length, repeatedly placed in random orientation and position on the visual image (a "randomly tossed" curve).

J. R. Singer of the University of California described a visual system which, by means of radial scanning, can recognise a two-dimensional object regardless of the visual angle it subtends or of its rotation in the visual field. However, this system requires that the object be centred in the visual field, so it is unlikely that the visual systems of living organisms, at least of vertebrates, use the same principle.

A different type of artificial visual system, designed by L. D. Harmon of Bell Telephone Laboratories, can recognise the convexity of a moving target. It consists of seven similar photocells, six tightly packed around the central one. The output of the central photocell produces inhibition at an artificial neuron; the output of the others, excitation. The neuron responds only to the passage of targets with radii within a particular size-range, according to the threshold setting. This system may correspond to the convexity detectors in the frog's eye, previously reported by Lettvin, Maturana, McCulloch, and Pitts.

E. E. Loebner demonstrated an artificial visual system consisting of a matrix of photoconductors, each connected in series with an electric energy source and an electroluminor. When light hits a photoconductor, this permits current to flow through the luminor and causes the luminor to emit light. By appropriate connexions and interconnexions of these elements it is possible to reproduce many of the functions of the vertebrate retina.

including all four detection functions found in the frog retina by Lettvin *et al.* It is possible that some of the circuits used in the model may be recognised in the living retina.

A machine capable of distinguishing among the spoken names of the digits "one", "two", and so on) was described by W. C. Dersch of International Business Machines Corporation. At least one of the principles on which it operates is known not to be used in the human auditory system. L. A. de Rosa, of International Telephone and Telegraph Corporation, presented a theory of the operation of the auditory system, explaining that its frequency discrimination is produced by an autocorrelation process rather than by mechanical filters. W. A. van Bergeijk, of Bell Telephone Laboratories, has built an artificial neuron network which he considers analogous to the spiral innervation of the cochlea and has measured signal loss as a function of simultaneous firing of several branches of the neuron. No similar measurements have been made on the actual nerve for comparison. He has also built an analog of a branching sensory nerve of the skin and has found that the analog and such nerves have comparable recruitment functions.

The highlight of the symposium was a group of talks by W. S. McCulloch and other mathematicians from his laboratory at the Massachusetts Institute of Technology and by K. K. Maitra of RCA Research Laboratories, on the general problem, "How simple can a neuron be and still, by proper interconnexion . . . perform all the known functions of the brain?" They started with the very simple McCulloch-Pitt neuron, which consists of a device that has many inputs which can carry either excitation or inhibition. It possesses a polar threshold such that the output is in one or the other of two states, depending on whether the algebraic sum of the inputs does or does not exceed the threshold value.

M. Blum considered the general question of what logical functions could be performed by simple networks of such neurons. He showed that if the number of inputs (such as signals from different sense organs) to a neural net is large, the number of logical functions which the net can perform approaches one-quarter of the totality of logical functions. This should certainly be enough to perform the limited number of logical functions which are known to be carried out by the brain.

A. N. Verbeek showed how to produce reliable computation with a "noisy", unstable neuron having four sources of trouble: variations in the signal strength of the inputs, faulty connexions, variations in internal threshold, and inability to propagate its output signal. He used triplet networks made up of three of the simple neurons, all the inputs to the triplet going in parallel to two of the neurons and their outputs going to the third neuron, whose output was the output of the triplet. Signals from each input were connected in parallel to each of many triplets. Each of these performs the logical operation, and the output of all the triplets goes to a neuron which acts as a majority decide, taking the outputs, comparing them, and deciding which is correct according to the output signals of the majority. If each neuron is capable of producing an error 5% of the time, the upper limit of the probable error of such a net can be made less than one in 1 million by a combination of just thirty such redundant triplets. This work is of great significance, since up to now the only theoretical method of increasing reliability has been to put many elements in parallel wherever one element has been used in the original net. Von Neumann has shown that to achieve a reliability of one error in a million by this older method with neurons which produce an error 5% of the time would require a net of about 20,000 neurons.

Cowan presented the mathematical logic he has developed for dealing with the behaviour of nets of neurons carrying on logical computations in the presence of noise. He was able to represent a general noisy computation scheme and to calculate the amount of signal that came through.

K. K. Maitra presented an extension of the work of Verbeek in the design of nets which reliably perform logical operations even though the neurons and connexions of the net may be unreliable. He developed a simplified mathematical symbolism for describing the manipulations of each triplet network. He was able to show that where a certain logical function is desired from the triplet, this function can be achieved with the greatest reliability by making the triplet from a combination of neurons each having a particular logical function, determined by a process he could specify. In a similar way he was able to show that if triplets are combined into triplet networks and these in turn into larger triplets, and so on, a minimum probability of error is found in networks made by three or four orders of such tripletting. When instead of tripletting the triplets he duplexed them, this gave increasing reliability with increasing order of duplexing up to any arbitrary level of reliability. Thus, it is possible in theory to design networks with unreliable neurons which will give any desired reliability of performance.

In a delightful summarising talk, H. von Foerster of the University of Illinois pointed out the importance of this work on reliability. It permits the achievement of increased reliability in a system not by increasing the reliability of the components and connexions but, more economically, by multiplexing unreliable components.

At the end of the symposium a final question was presented to McCulloch. He was asked, in effect, whether the people working on information processing would not some day, like the nuclear physicists today, have cause to regret the social consequences of their work. McCulloch replied that he was convinced that it was in man's nature to develop both the socially good and the socially bad consequences of any invention. He fully expects that the world will be booby-trapped by the use of these and other sciences, but it is his firm hope that by making available information-handling devices of great capacity man will prevent the detonation of that booby-trap through misinformation.

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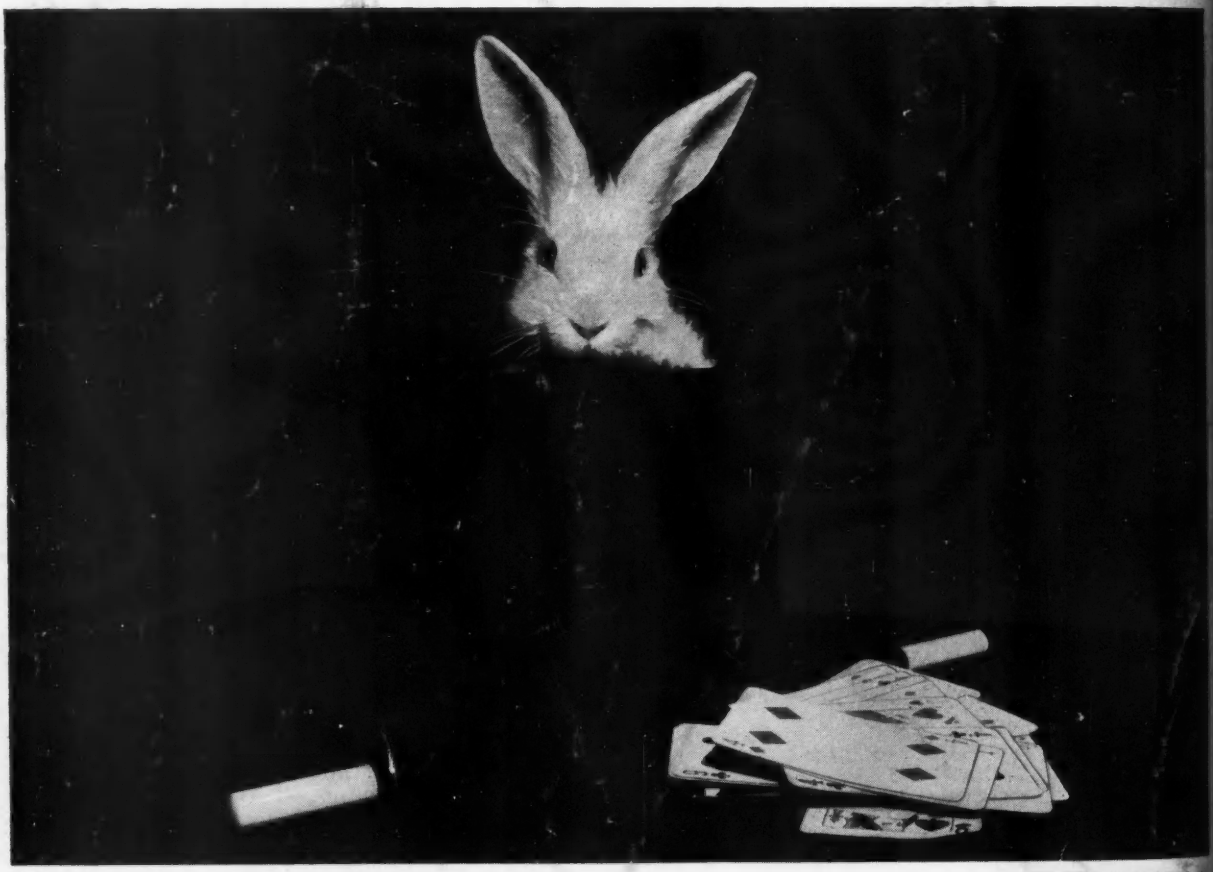

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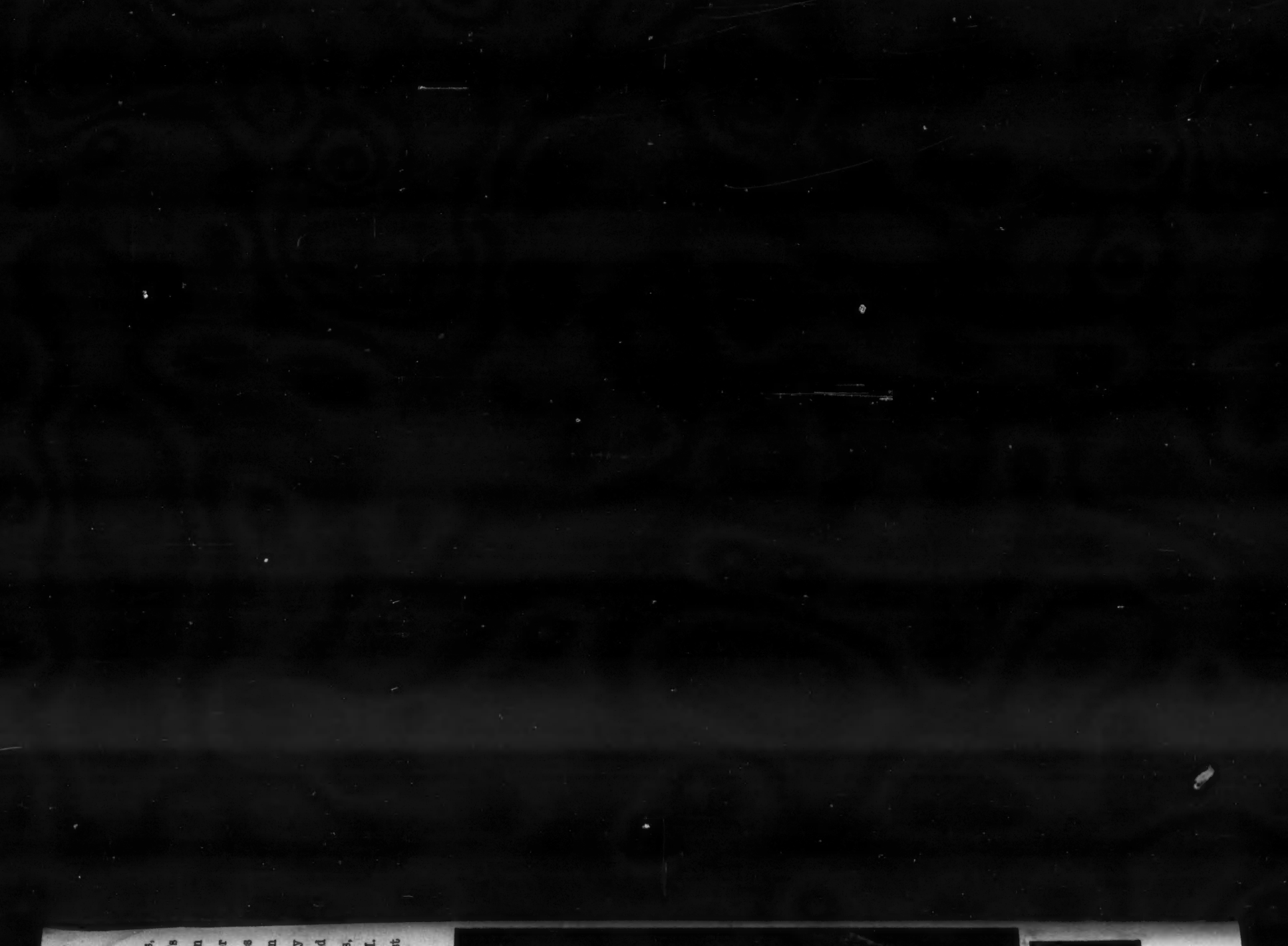
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